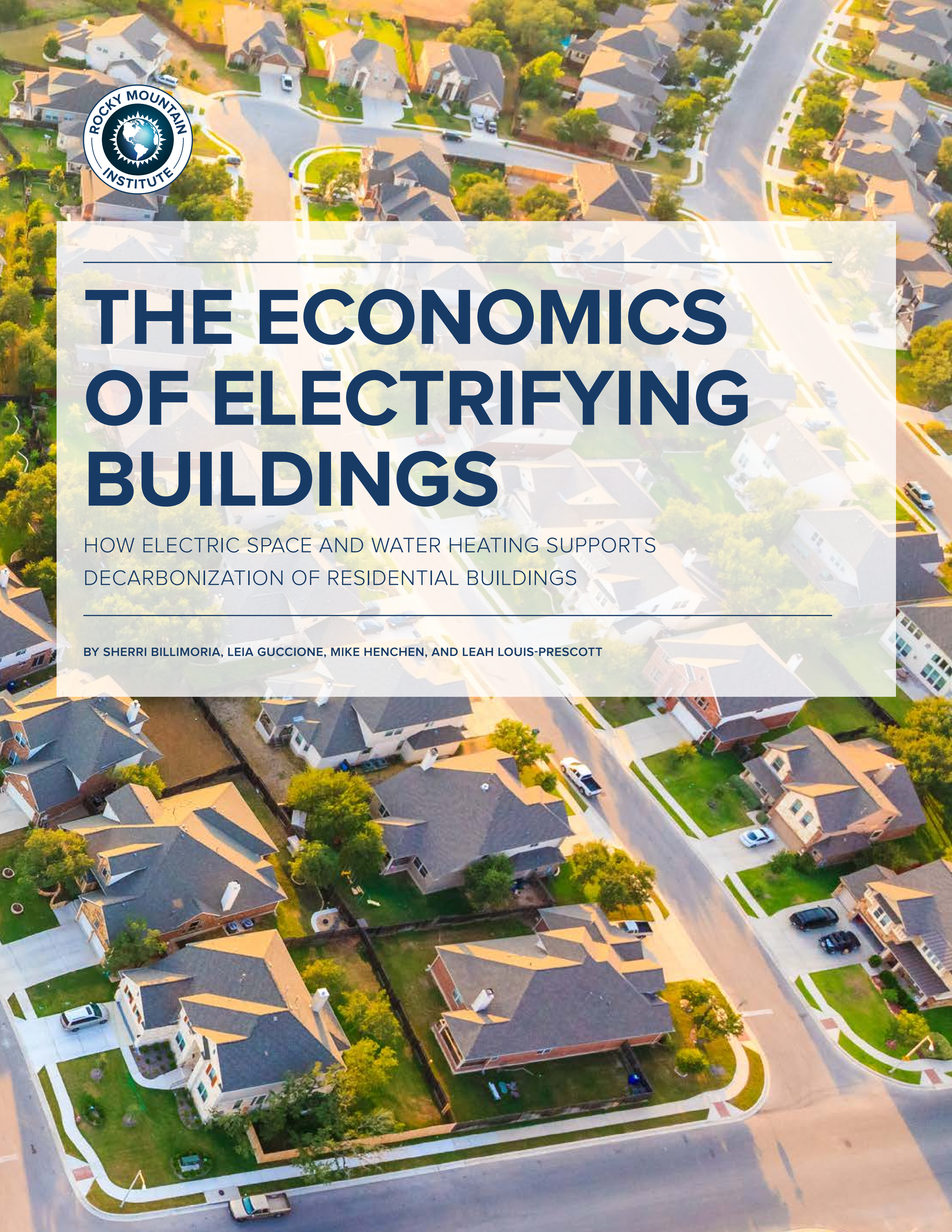

# THE ECONOMICS OF ELECTRIFYING BUILDINGS

## HOW ELECTRIC SPACE AND WATER HEATING SUPPORTS DECARBONIZATION OF RESIDENTIAL BUILDINGS

**BY SHERRI BILLIMORIA, LEIA GUCCIONE, MIKE HENCHEN, AND LEAH LOUIS-PRESCOTT**

# AUTHORS & ACKNOWLEDGMENTS


## AUTHORS
Sherri Billimoria, Leia Guccione, Mike Henchen, and Leah Louis-Prescott

** Authors listed alphabetically. All authors from Rocky Mountain Institute unless otherwise noted.*

## ADDITIONAL CONTRIBUTORS
Alisa Petersen, RMI

## CONTACTS
Sherri Billimoria, sbillimoria@rmi.org
Mike Henchen, mhenchen@rmi.org



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Mark Dyson, RMI
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Dan Steinberg, NREL
Charlie Stephens, Northwest Energy Efficiency Alliance
Jenna Tatum, NYC Mayor's Office of Sustainability
Neil Veilleux, Meister Consultants
Geoff Wickes, Northwest Energy Efficiency Alliance
Larry Zarker, Buildings Performance Institute
Hayes Zirnhelt, RMI

# ABOUT US

## ABOUT ROCKY MOUNTAIN INSTITUTE

Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; Washington, D.C.; and Beijing.

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# EX EXECUTIVE SUMMARY

# EXECUTIVE SUMMARY

Seventy million American homes and businesses burn natural gas, oil, or propane on site to heat their space and water,[1] generating 560 million tons of carbon dioxide each year—a tenth of total US emissions.[2] Now, with an increasingly low-carbon electric grid comes the opportunity to meet nearly all our buildings' energy needs with electricity,[i] eliminating direct fossil fuel use in buildings and making the gas distribution system—along with its costs and safety challenges—obsolete. Further, electric space and water heating can be intelligently managed to shift energy consumption in time, aiding the cost-effective integration of large amounts of renewable energy onto the grid. And reaching "deep decarbonization" goals of 75% or greater reduction in greenhouse gas emissions will require eliminating most or all of the $CO_2$ produced by furnaces and water heaters across the country, alongside other measures across the economy.

Achieving this vision will require massive market transformation, including discontinuing the expansion of the gas distribution system, widespread adoption of new appliances in homes and businesses across the country, and new markets for intelligent devices to provide flexible demand to the grid. Eleven million households burn oil or propane for heat—the most carbon intensive and costly fuels—and another 56 million burn natural gas.[3] The most efficient electric devices—heat pumps for space and water heating—have small market share today; many homes need additional electrical work to accommodate them; and consumer awareness of this heating technology option is low.

In this paper, we analyze the economics and carbon impacts of the electrification of residential space and water heating both with and without demand flexibility—the ability to shift energy consumption in time to support grid needs. We compare electric space and water heating to fossil fuels for both new construction and home retrofits under various electric rate structures in four locations: Oakland, California; Houston, Texas; Providence, Rhode Island; and Chicago, Illinois. We focus on the residential sector, which makes up the majority of carbon emissions from buildings' fossil fuel use,[4] but a similar market transformation will be needed in commercial buildings to meet deep decarbonization targets. Cooking, clothes drying, and other end uses are assumed to be electric in all cases.

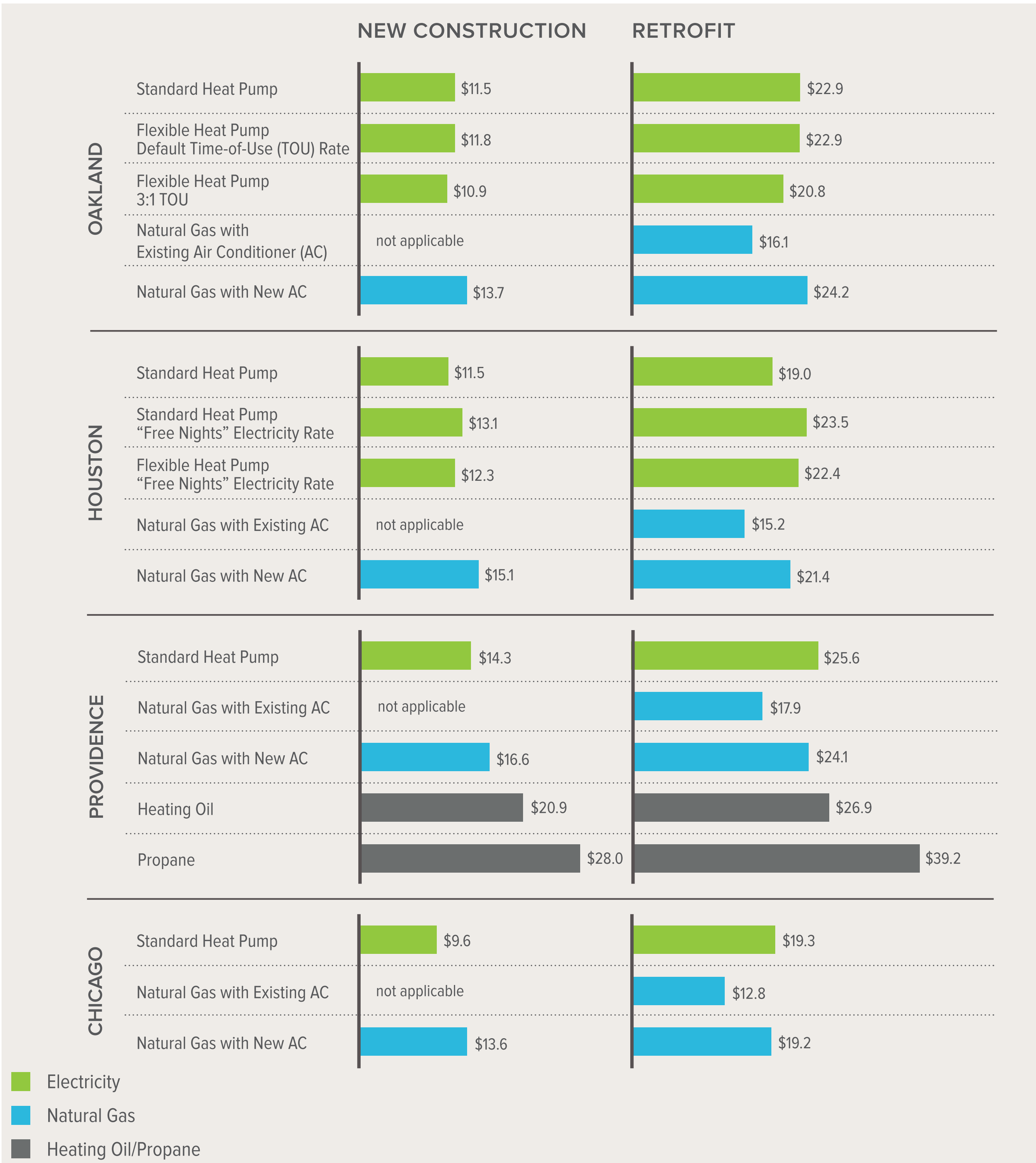
In many scenarios, notably for most new home construction, we find electrification reduces costs over the lifetime of the appliances when compared with fossil fuels. However, for the many existing homes currently heated with natural gas, electrification will increase costs at today's prices, compared to replacing gas furnaces and water heaters with new gas devices. We find electrification is cost-effective for customers switching away from propane or heating oil, for those gas customers who would otherwise need to replace both a furnace and air conditioner simultaneously, for customers who bundle rooftop solar with electrification, and for most new home construction, especially when considering the avoided cost of gas mains, services, and meters not needed in all-electric neighborhoods. Customers with existing gas service face higher up-front costs to retrofit to electric space and water heating compared with new gas devices, and either pay more for energy with electric devices—in the case of colder climates in Chicago and Providence—or save too little in energy costs to make up the additional capital cost—in the case of Houston and Oakland. Figure 1 illustrates this result, described in more detail in the body of the report.[ii]

[i] The carbon intensity of the US electric grid in 2017 was 25% lower than in 2007, down from 1,335 lb. $CO_2$/MWh to 1,002 lb. $CO_2$/MWh.

[ii] Our scenarios evaluate space heating, air conditioning, and water heating. Air conditioning is already powered by electricity, but its costs are important to include in electrification analysis, since heat pumps provide both heating and cooling and can replace both a furnace and air conditioner with a single device.

**FIGURE 1**

COMPARISON OF 15-YEAR NET PRESENT COSTS OF WATER HEATING AND SPACE CONDITIONING (THOUSAND $)



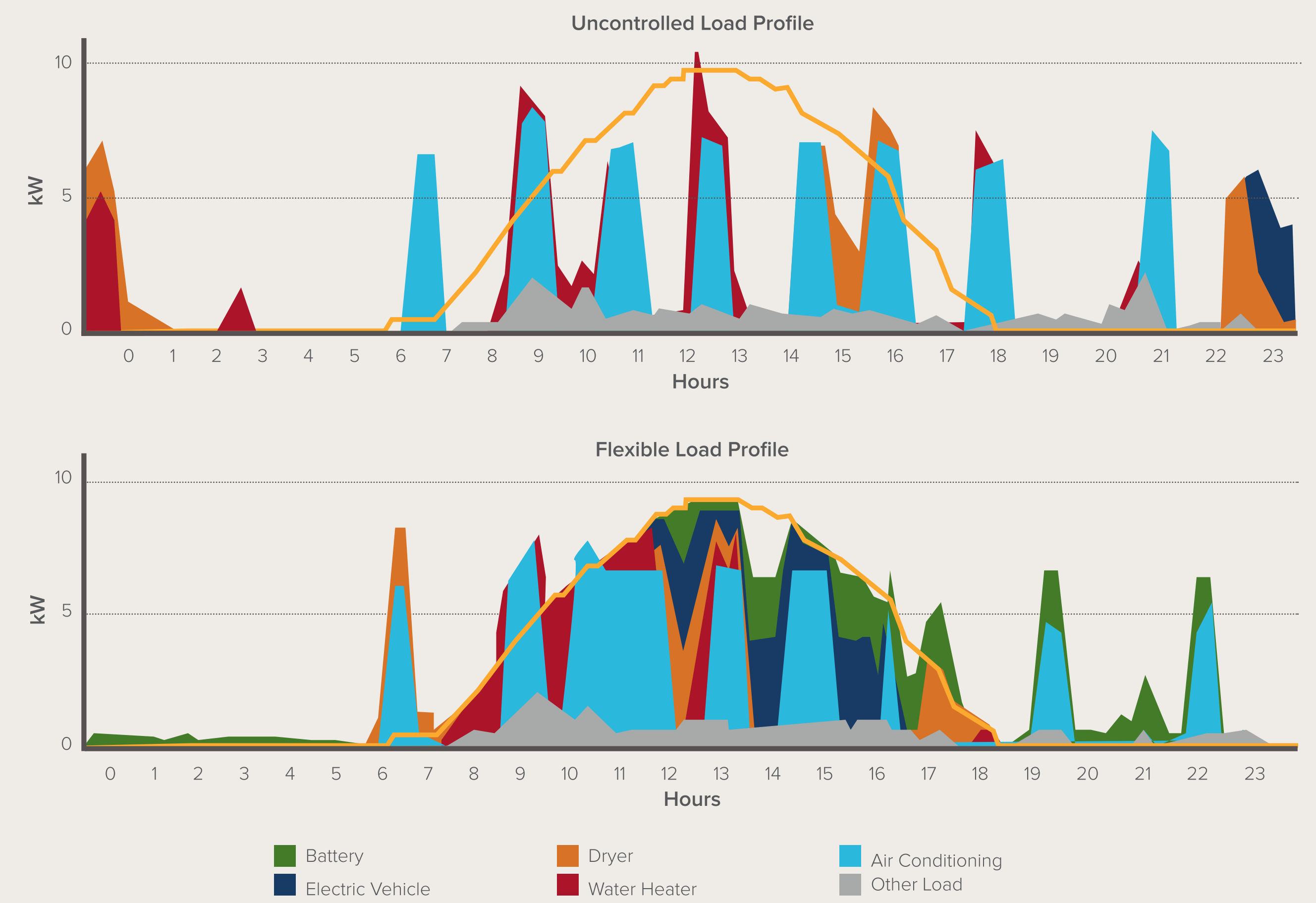
## WHAT IS DEMAND FLEXIBILITY?

Demand flexibility uses communication and control technology to shift electricity use across hours of the day while delivering end-use services (e.g., cool or warm air, hot water, electric vehicle charging) at the same or better quality but lower cost. It does this by applying automatic control to reshape a customer's demand profile continuously in ways that either are invisible to or minimally affect the customer, and by leveraging more-granular rate structures that monetize demand flexibility's capability to reduce costs for both customers and the grid.

For water heating and space conditioning, flexible devices preheat or precool during periods of low-cost electricity, in order to use less electricity during high-cost periods.

**FIGURE 2**

DEMAND FLEXIBILITY CAN SHIFT LOADS INTO TIMES OF HIGH RENEWABLE OUTPUT OR LOW COST




Many factors could improve the cost-effectiveness of electrification compared to gas in the future. The purchase price of heat pump devices is expected to decline as the market grows and manufacturers realize economies of scale. The value of electric demand flexibility is likely to increase as variable renewables grow on the system, increasing the price spreads in electricity markets—customers' ability to capture this value with intelligent devices can reduce the lifetime costs of electrification but depends on new rate designs and utility programs. Carbon pricing or other climate policy may impose additional costs on natural gas supply. Or gas commodity prices may change in unpredictable ways in the future.

Electrification already reduces carbon with today's electric grid in all but the most coal-heavy systems. This is true in comparison to not only heating oil and propane, but also to natural gas. Figure 3 illustrates this result, showing emissions reductions in Oakland, Houston, and Providence. Because the electric grid serving Chicago has coal power as its marginal generator most of the year, the short-term impact of electrification increases carbon emissions.[iii] With continued retirement of coal plants, however, the long-term impact is expected to swing in favor of electrification in Chicago and nationally.

## SUMMARY OF RECOMMENDATIONS

Electrification of space and water heating presents a viable pathway to deep decarbonization, already reduces carbon in all but the most coal-dominated regions, can support renewable energy integration with the proper control strategies, and is lower cost than fossil fuel alternatives in several key scenarios including new construction and retrofit from propane or heating oil. Even regions that are coal-dominated today are seeing rapid retirement of coal plants, making

[iii] For a detailed description of our approach to marginal carbon accounting, see page 23.

electrification more attractive. There were almost 7 GW of coal retirements and no new coal plants in 2017,[5] and more than 11 GW of coal plants are scheduled to retire in 2018.[6] However, many households currently heated with natural gas will not find it cost-effective to switch from furnaces to electric heat pumps at today's prices. To capture the near-term benefits of fuel switching where most beneficial, and to prepare for a long-term approach that includes widespread cost-effective electrification, we offer five recommendations for regulators, policymakers, and utilities:

1. **Prioritize rapid electrification of buildings currently using propane and heating oil** in space and water heating. Although these represent less than 10% of US households, they account for more than 20% of space and water heating emissions. Electrification is very cost-effective for propane customers, and has a comparable cost to heating oil depending on local pricing. Electrifying these homes in the near term can build scale and market maturity to support even more widespread electrification in the future.

2. **Stop supporting the expansion of the natural gas distribution system, including for new homes**. This infrastructure will be obsolete in a highly electrified future, and gas ratepayers face significant stranded asset risk in funding its expansion today. Furthermore, electrification is a lower-cost and lower-carbon solution than extending natural gas, either to new or existing homes.

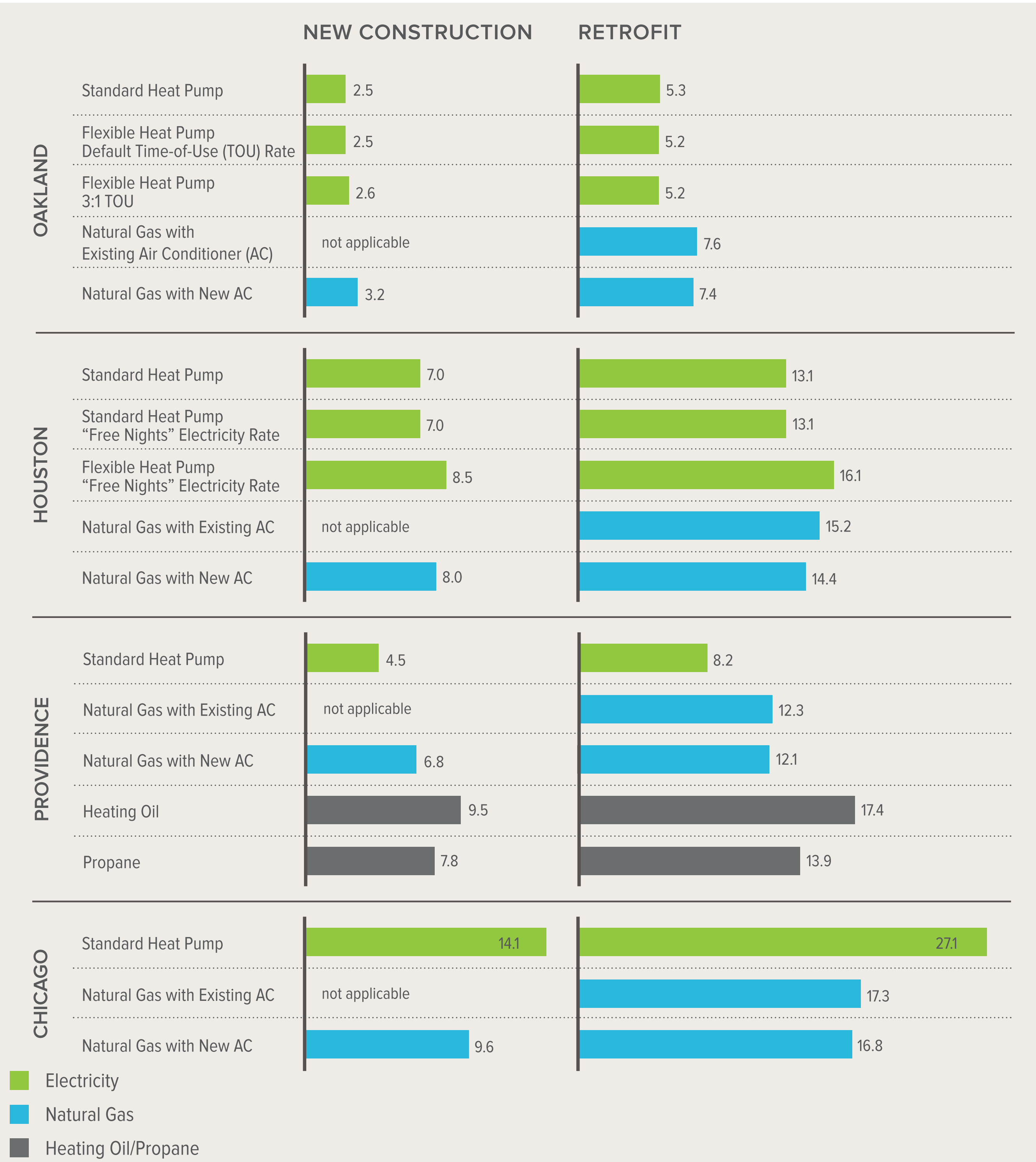
3. **Bundle demand flexibility programs, new rate designs, and energy efficiency with electrification initiatives** to effectively manage peak load impacts of new electricity demand, especially in colder climates that will see increased peaks in winter electricity demand with electrified heating.

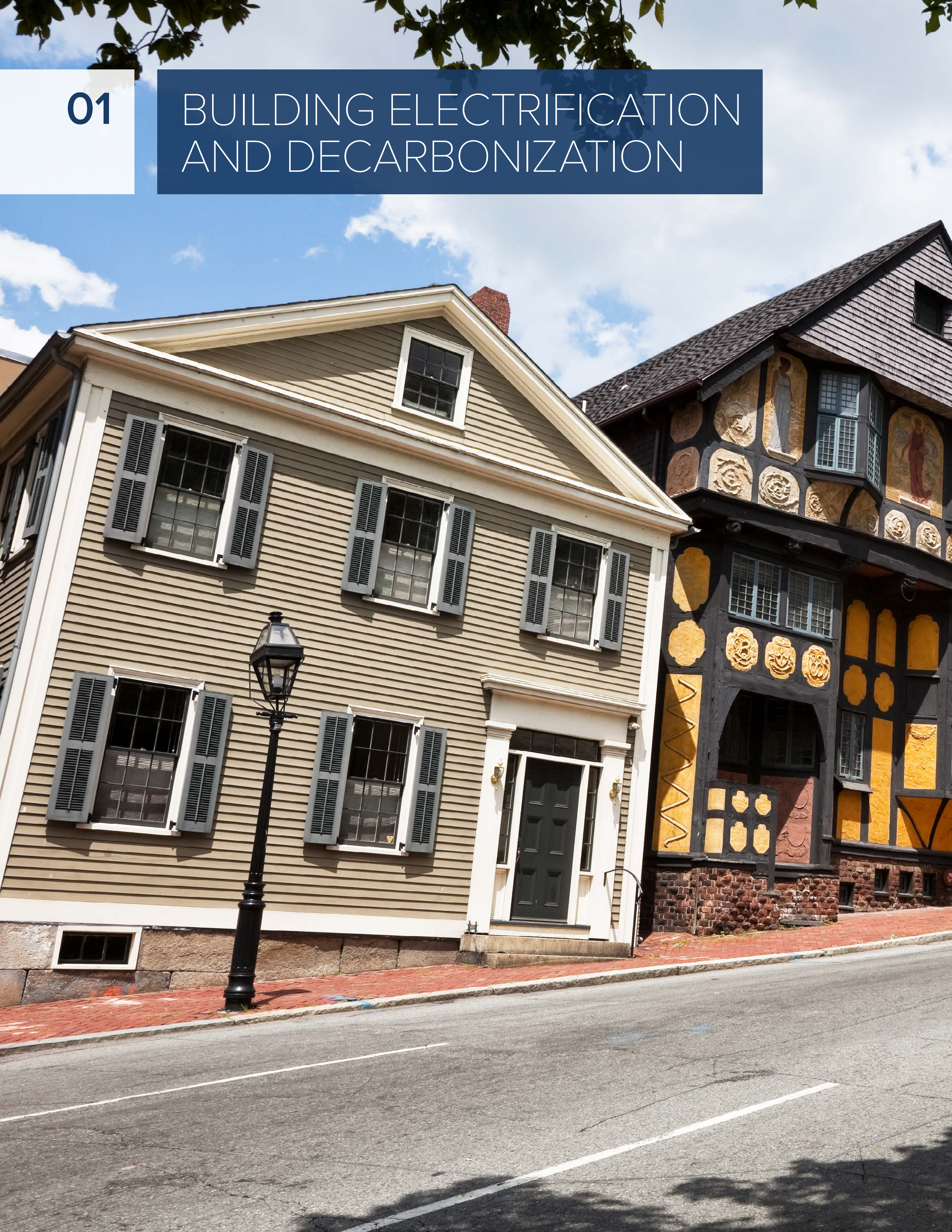
4. **Expand demand flexibility options for existing electric space and water heating loads**. Only 1% of the 50 million existing electric water heaters in the US participate in demand response. As widespread electrification adds loads, particularly in winter, effective demand management will mitigate system costs and aid renewables integration.

5. **Update energy efficiency resource standards and related goals**, either on the basis of total energy reduction across both electricity (in kWh) and gas (in therms), or on the basis of emissions reductions across both electric and gas programs. Otherwise, successful electrification could penalize utilities for not reducing electricity demand, even when it provides cost and carbon benefits.

**FIGURE 3**

ANNUAL CARBON EMISSIONS BY SCENARIO (THOUSAND LB. $CO_2$)





# 01 BUILDING ELECTRIFICATION AND DECARBONIZATION

# BUILDING ELECTRIFICATION AND DECARBONIZATION

US buildings' on-site use of fossil fuels contributes 560 million tons of $CO_2$ emissions annually, nearly 10% of total national greenhouse gas emissions.[7] Meanwhile, 14 US states have formally committed to deep decarbonization reductions of 75% or greater by mid-century in order to support global efforts to limit average temperature increase to 2°C.[8] Reaching these aggressive state goals will require drastic reductions across all sectors, including buildings' fossil fuel use. Multiple studies have identified the electrification of buildings (along with transportation and many industrial end uses) combined with decarbonization of power generation as critical to achieving these deep decarbonization targets.[9] Moving the US electricity system to power generation that emits zero carbon will only reduce total US emissions 30%. Widespread electrification of buildings, ground transportation, and half of industry would boost reductions to more than 70% if powered by zero-carbon electricity. Even deeper reductions will require additional efficiency improvements or other reductions in remaining industrial end uses, agriculture, air travel, and shipping.[10]

**FIGURE 4**

CARBON EMISSIONS OF FOSSIL FUEL END USES IN US BUILDINGS, 2015, MT $CO_2E$

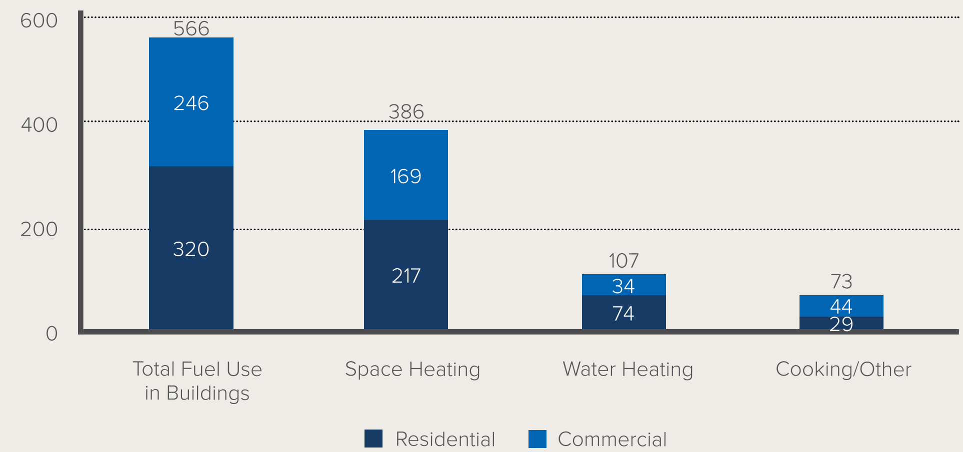
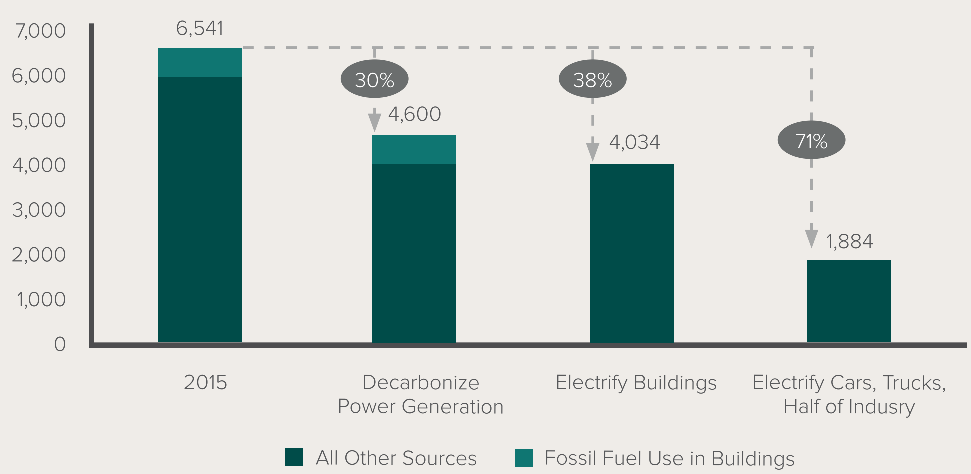



**FIGURE 5**

US ECONOMY-WIDE GREENHOUSE GAS EMISSIONS AND DECARBONIZATION OPTIONS, MT $CO_2E$[11]



# 02 OVERVIEW OF SCENARIO ANALYSIS

# OVERVIEW OF SCENARIO ANALYSIS

- We modeled one year of energy use for water heating, space heating, and air conditioning in a single-family home to determine the annual carbon impact and the 15-year net present cost of each scenario. Our 34 scenarios differed by the variables described in Figure 6.

## HEAT PUMP TECHNOLOGY

Heat pumps use electricity to heat and cool buildings. In summer, they operate as air conditioners, moving heat from inside a building to outside. In winter, they operate in reverse, moving heat from outside to inside. Because they move heat rather than generate heat, heat pumps are more efficient than electric furnaces and baseboard heating.[12] More than 12 million US households already use heat pumps as their primary source of heat, mostly in the Southeast.[13] In years past, heat pumps were only effective in mild climates, unable to operate at temperatures below freezing. Today hundreds of models can operate efficiently at 5°F, and some can provide heat in temperatures as low as -13°F.[14] In this report we evaluate air-source heat

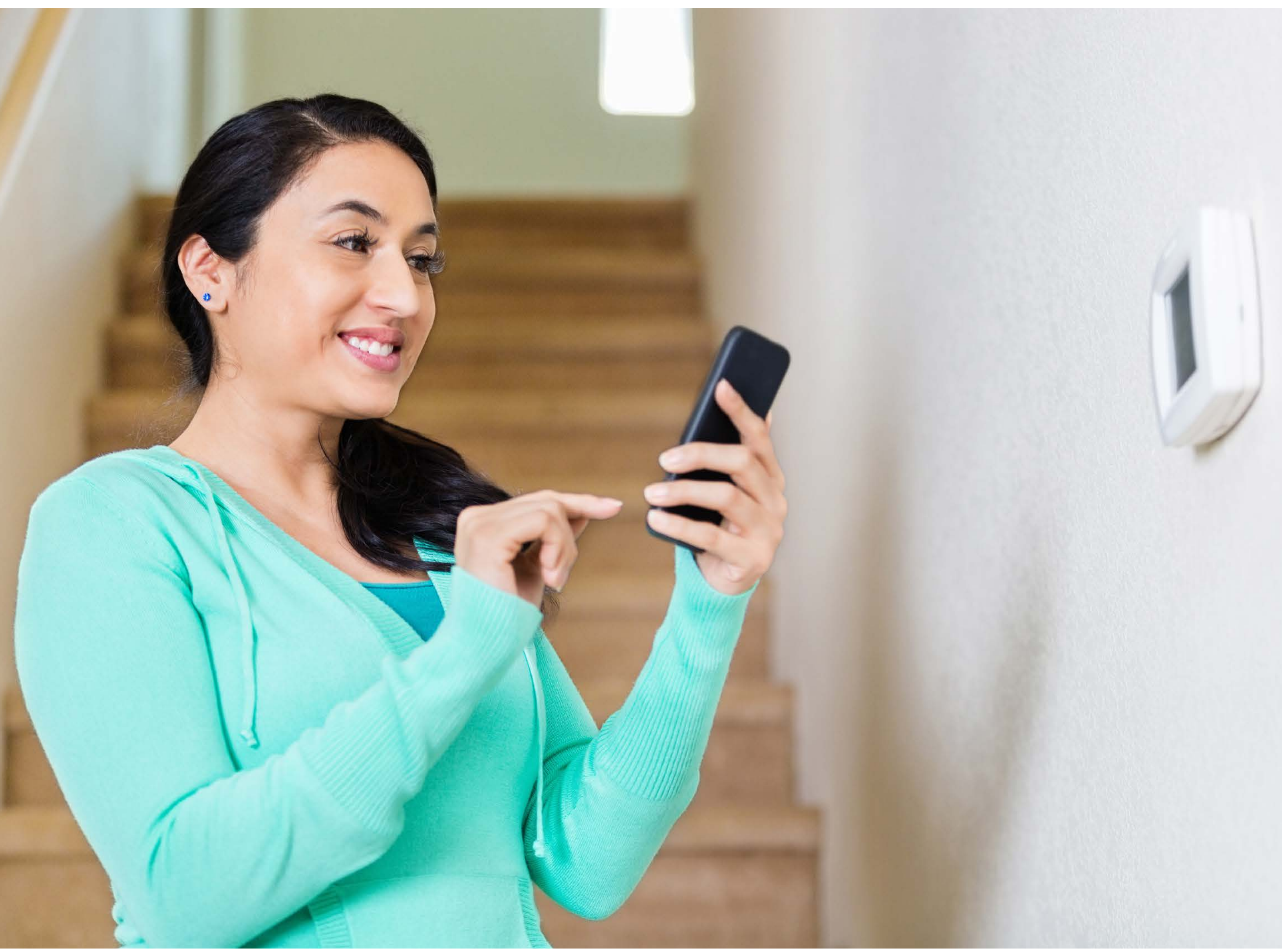
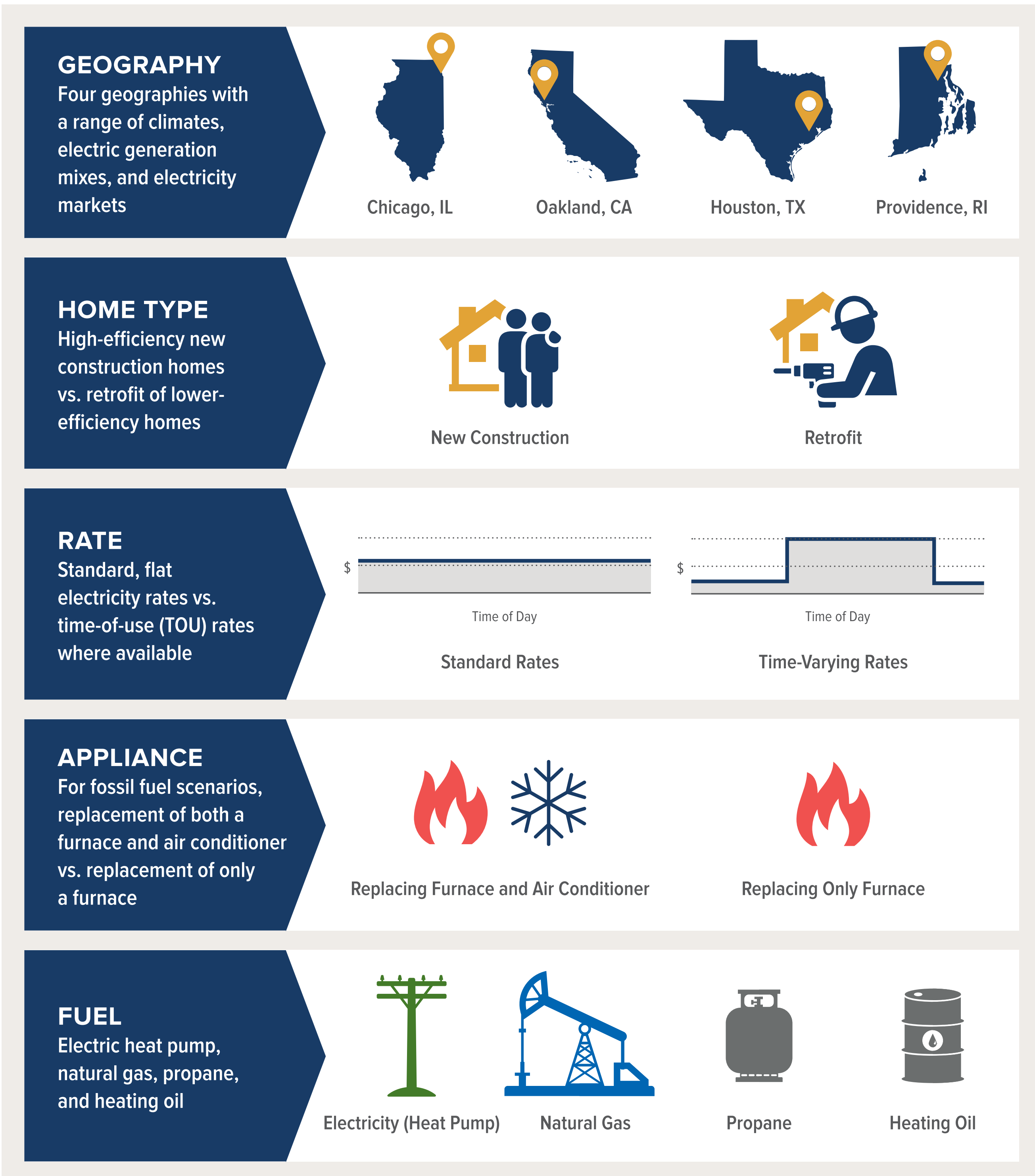


**FIGURE 6**

SCENARIO CHARACTERISTICS



pumps capable of providing central air conditioning and heating. Several other technologies that can also provide efficient electric heat but were not evaluated in this report include the following:

- **Ductless mini-split heat pumps** are air-source heat pumps that heat and cool a single room, rather than an entire home through ducts. Mini-splits can be good solutions for homes without central heating and air conditioning. Cold climate mini-splits have already seen success in electrification programs in the Northeastern US, with more than 70,000 units installed.[15]

- **Ground-source heat pumps**, also called geothermal heat pumps, exchange heat with the ground rather than the air surrounding a building. This is advantageous in cold climates, where the ground temperature remains moderate even when the air temperature is very cold, and ground-source heat pumps consume less energy on the coldest days in particular. Ground-source heat pumps have historically been significantly more expensive than air-source heat pumps due to the need for drilling and underground equipment installation, but new innovation in this market may make these devices more cost-effective in the near future.[16]

- **$CO_2$ refrigerant heat pumps** use carbon dioxide in place of traditional refrigerants like R-410a. These systems are highly efficient and avoid the use of HFC refrigerants, which have high global warming impacts if leaked. While common in Japan and Southeast Asia, these systems do not yet have a significant US market presence.[17]

- **Efficient low-lift heat pumps** have been shown to achieve heating coefficients of performance as high as 9. The term “low-lift” refers to the temperature difference between the source (e.g., outside air or underground) and the space or water that is being heated. Swiss researchers demonstrated technology that used deep (300 meters or greater) underground probes combined with efficient underfloor heating systems to provide a temperature lift of 20°C (36°F), from a deep underground source at 46°F to heat water to 82°F for underfloor heating.[18]

# 03 FINDINGS

# FINDINGS

## COST-EFFECTIVENESS OF ELECTRIFICATION

Electrifying buildings is cost-effective today in some scenarios, but more expensive for most existing natural gas customers. While costs can vary substantially depending on individual home characteristics, our analysis found several consistent results. Electrification is generally cost-effective for oil and propane customers, for both new construction and retrofits. For newly constructed homes, heat pumps are usually the lowest-cost option, particularly since a heat pump provides both heating and air conditioning, and these homes avoid the cost of both furnaces and air conditioners. For retrofits of existing homes, heat pumps can be lower cost than replacing both furnace and air conditioner separately. For homes currently using natural gas heating and only needing to replace a gas furnace, it is usually more expensive to electrify than to stick with gas. Demand flexibility that optimizes for typical time-of-use rates can reduce energy costs, but is not usually significant enough to tip the scales in favor of electrification. Different pricing structures that capture more of these devices' flexible capability could provide much greater value and further improve customer economics. The costs presented in Figure 7 include space heating, water heating, and air conditioning, and are presented on the basis of 15-year net present cost.

## CARBON IMPACTS OF ELECTRIFICATION

Electrification already reduces carbon with today's technology and electric grid in all but the most coal-heavy regions.[iv] In decades past, building electrification meant installing inefficient electric resistance devices or older heat pumps that performed poorly at cold temperatures, powered by a coal-dominated grid. Between the inefficiency of the devices and the high carbon intensity of the power generation, heating with electricity was dirtier and more expensive than burning natural gas on site. But now, efficient modern heat pumps combined with a lower-carbon grid have created a new opportunity to decarbonize with electrification.

In Houston, Oakland, and Providence, heat pump systems produce less carbon emissions than natural gas systems today. When compared to heating oil and propane in Providence, the carbon savings from fuel switching are even more dramatic. Because Chicago's grid is largely coal-fired on the margin, at least in the short term, heat pump systems currently have higher emissions than natural gas systems. With the continued pace of coal plant retirement, we expect this to change in favor of electrification. Reciprocally, in regions that already have a relatively low-carbon generation mix—such as Rhode Island, where the marginal emissions intensity averages 815 lb./MWh—heat pump systems are significantly less carbon intensive than natural gas.

Note that we include air conditioning loads in our analysis, even though they are already electrified. This is because heat pumps function as both air conditioners and heaters, and often provide air conditioning at very high efficiency relative to existing AC systems. Customers facing the prospect of replacing both an air conditioner and furnace can save installation cost by choosing a heat pump for both functions, and often reduce carbon further due to the efficiency improvement in air conditioning the heat pump provides.

[iv] For more detail on our carbon analysis and an assessment of the effects of methane leakage, see page 26.

**FIGURE 7**

COMPARISON OF 15-YEAR NET PRESENT COSTS OF WATER HEATING AND SPACE CONDITIONING (THOUSAND $)

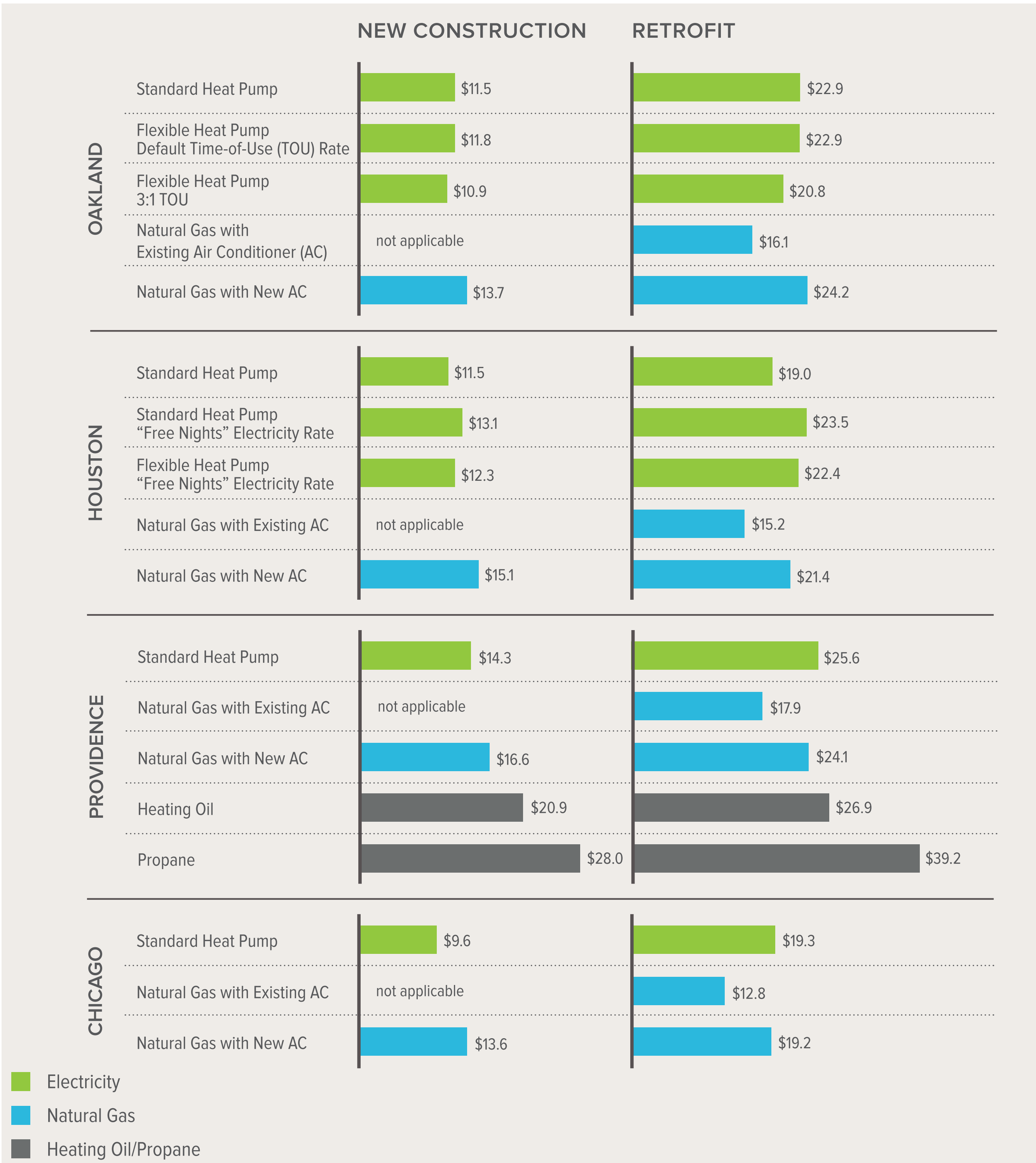
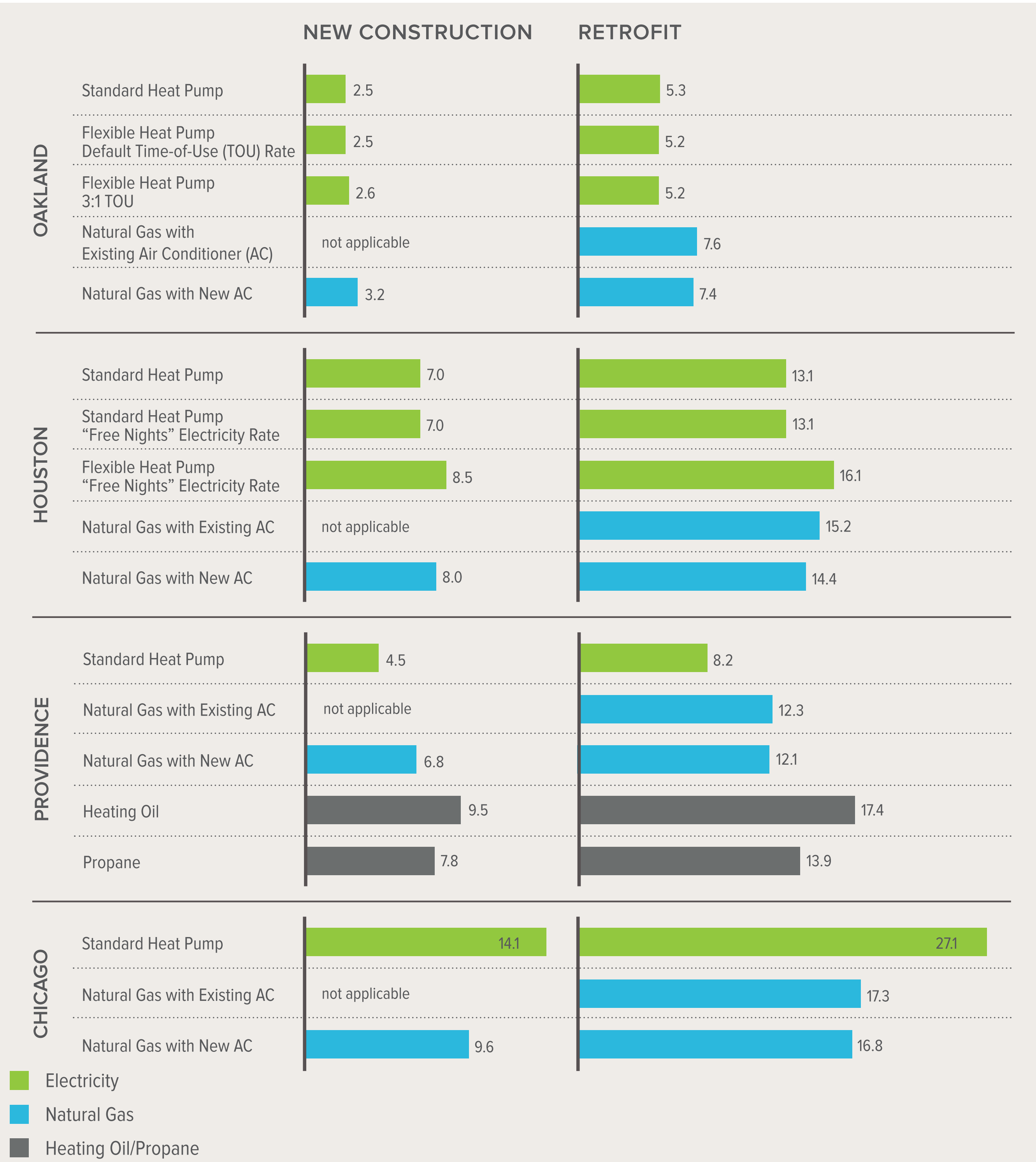


**FIGURE 8**

ANNUAL CARBON EMISSIONS BY SCENARIO (THOUSAND LB. $CO_2$)



## APPROACHES TO QUANTIFYING CARBON EMISSIONS

Our analysis uses a short-term marginal carbon approach. Here we discuss the merits of that approach compared to two alternatives: average carbon and long-term marginal carbon.

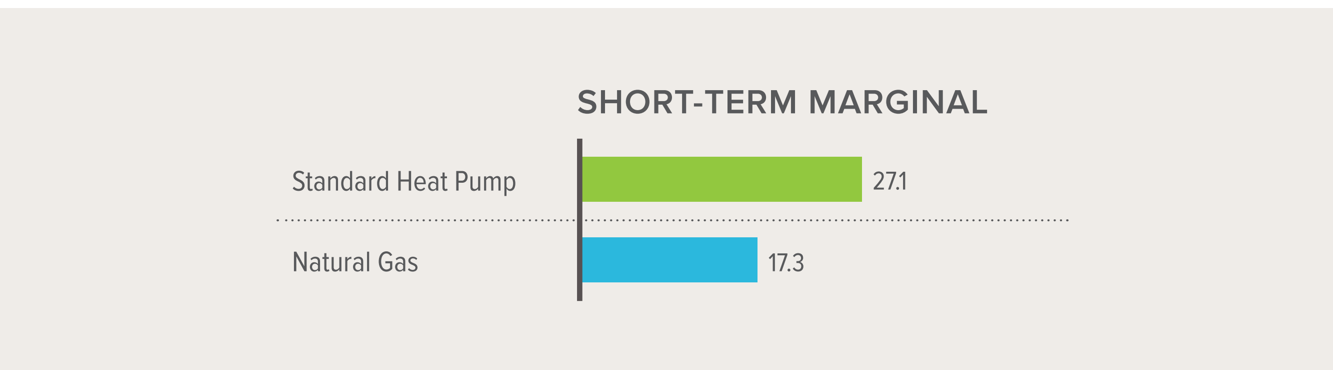
### SHORT-TERM MARGINAL CARBON:

This approach, used throughout this report, considers what generator is "on the margin" in a particular system in each 15-minute increment for a year.[v] This marginal generator is the power plant that must increase its output if demand increases. In Chicago, the dominant marginal generation throughout the year is coal, producing around 2,166 lb. $CO_2$/kWh. So, a new electric heating load would have the effect of increasing immediate output from these coal plants and adding emissions accordingly.

This approach has the benefit of considering the changes that load growth has on the grid rather than considering the generation that would take place regardless of changes in load (as in the average carbon approach). However, it does have drawbacks. First, it does not consider changes in the grid over time, namely that coal plants are retiring around the country, and the grid that future heat pumps will draw from will look different than the grid in 2016. And second, this short-term approach does not consider how increases in load, especially those with demand flexibility that can coincide with periods of high wind or solar output, affect decisions about what resources to add to the system.

**FIGURE 9**

COMPARISON OF SHORT-TERM MARGINAL ANNUAL CARBON EMISSIONS IN CHICAGO, RETROFIT (THOUSAND LB. $CO_2$)



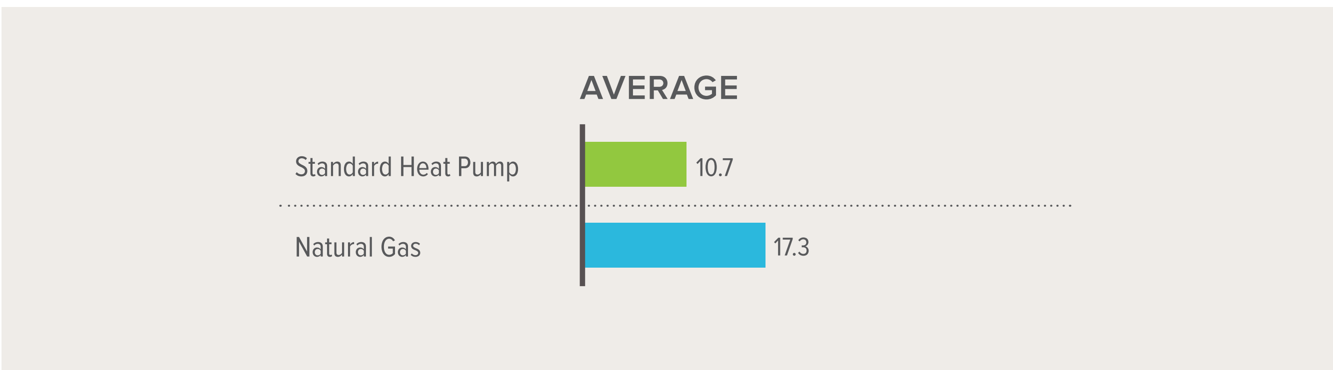

[v] Our data comes from WattTime and reflects actual 2016 grid operations in each geography.

### AVERAGE CARBON:

This approach applies the average carbon intensity of a state's grid to the increase in load from electrification. The drawback of this approach is that it reflects the generation that already exists without electrification rather than considering the impact of added load. Therefore it does not reflect the actual emissions resulting from new heat pump loads. In Illinois, for example, the average carbon intensity—848 lb./MWh, reflecting a mix of natural gas, coal, and renewables—would suggest heat pumps are significantly less carbon-intensive than natural gas systems.

**FIGURE 10**

COMPARISON OF ANNUAL AVERAGE CARBON EMISSIONS IN CHICAGO, RETROFIT (THOUSAND LB. $CO_2$)



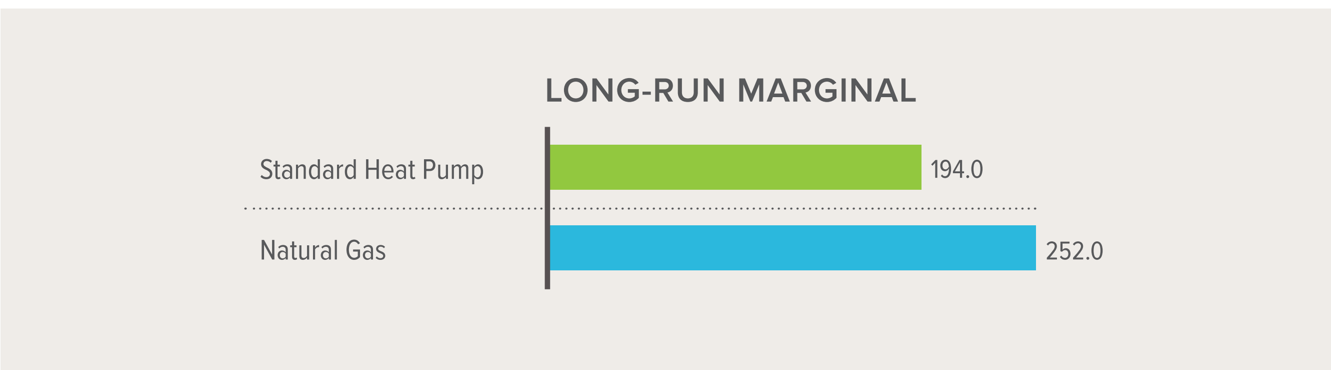
### LONG-TERM MARGINAL CARBON:

This approach considers both which plants must increase their output immediately in response to new load, and the long-term changes in plants' capacity factors, retirement schedules, and additions of new generation in response to load growth. The long-term marginal carbon approach was beyond the scope of this study.

However, as an illustrative hypothetical, we consider the following scenario for Chicago: that some coal plants increase capacity factor immediately or delay retirement in response to load growth, but that many still retire, while increased load is met by natural gas and wind. While the carbon impact in the first year would be coal-heavy, in future years the addition of new gas and wind generation to meet load growth would come into play. The long-term carbon impact can be conveyed as the combined impact of these factors over a 15-year lifetime of the devices. For our hypothetical, we assume this combined impact is equal parts coal, natural gas, and wind, resulting in a beneficial outlook for electrification, as shown in Figure 11.

**FIGURE 11**

COMPARISON OF LIFETIME LONG-RUN MARGINAL CARBON EMISSIONS IN CHICAGO, RETROFIT (THOUSAND LB. $CO_2$)



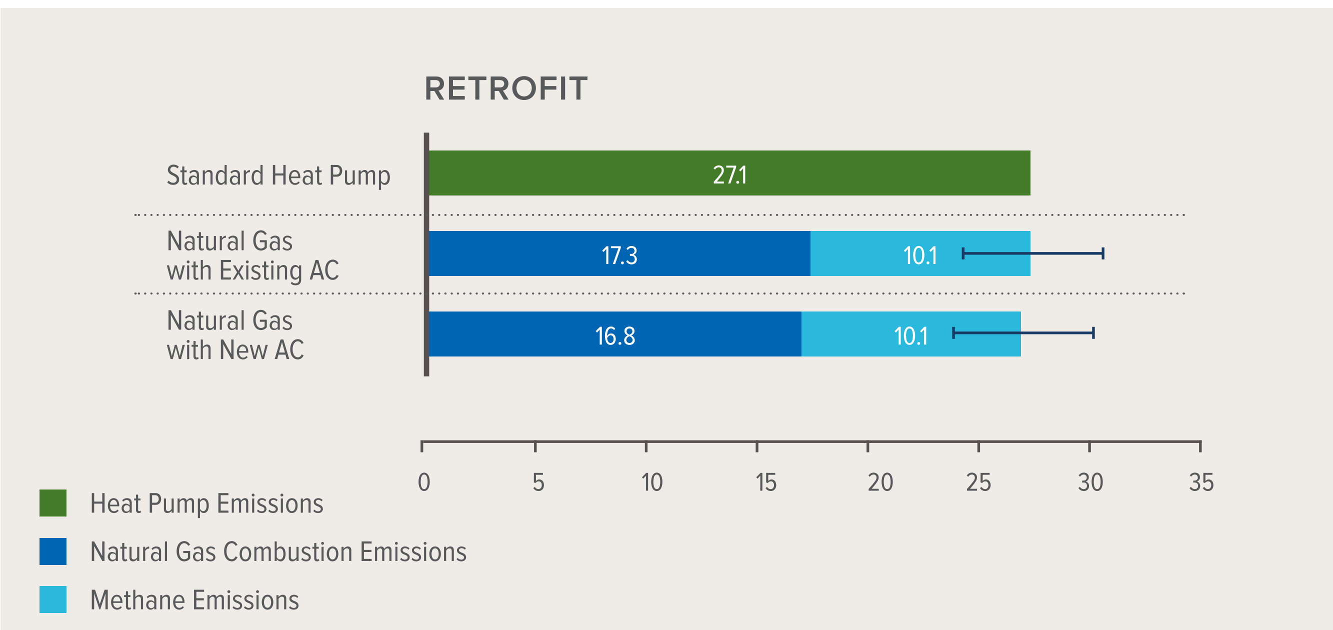
## METHANE LEAKAGE

Natural gas, composed primarily of methane, is a powerful greenhouse gas if emitted directly into the atmosphere, driving 85 times more warming than carbon dioxide over a 20-year period.[19] The production and distribution of natural gas is known to leak methane, increasing the global warming impact of natural gas beyond the value typically considered in gas combustion, whether in a power plant, furnace, or water heater. We account for that impact here, using leakage estimates ranging from 2%, EPA's 2016 estimate, to 3.8%, from Robert Howarth's research at Cornell.[20]

In Chicago, the prevalence of coal plants as marginal generators suggests that electrification is significantly more carbon intensive than natural gas systems. However, accounting for methane emissions significantly increases the emissions impact of natural gas systems in relation to coal emissions. Due to the increased emissions of natural gas systems with methane leakage, heat pump systems in Chicago now have comparable emissions impacts to natural gas use in the home. Heat pumps range from 12% more carbon intensive to 11% less carbon intensive than natural gas systems, depending on the leakage rate used.

**FIGURE 12**

ANNUAL EMISSIONS OF HEATING IN CHICAGO RETROFIT WITH METHANE LEAKAGE (THOUSAND LB. $CO_2E$)

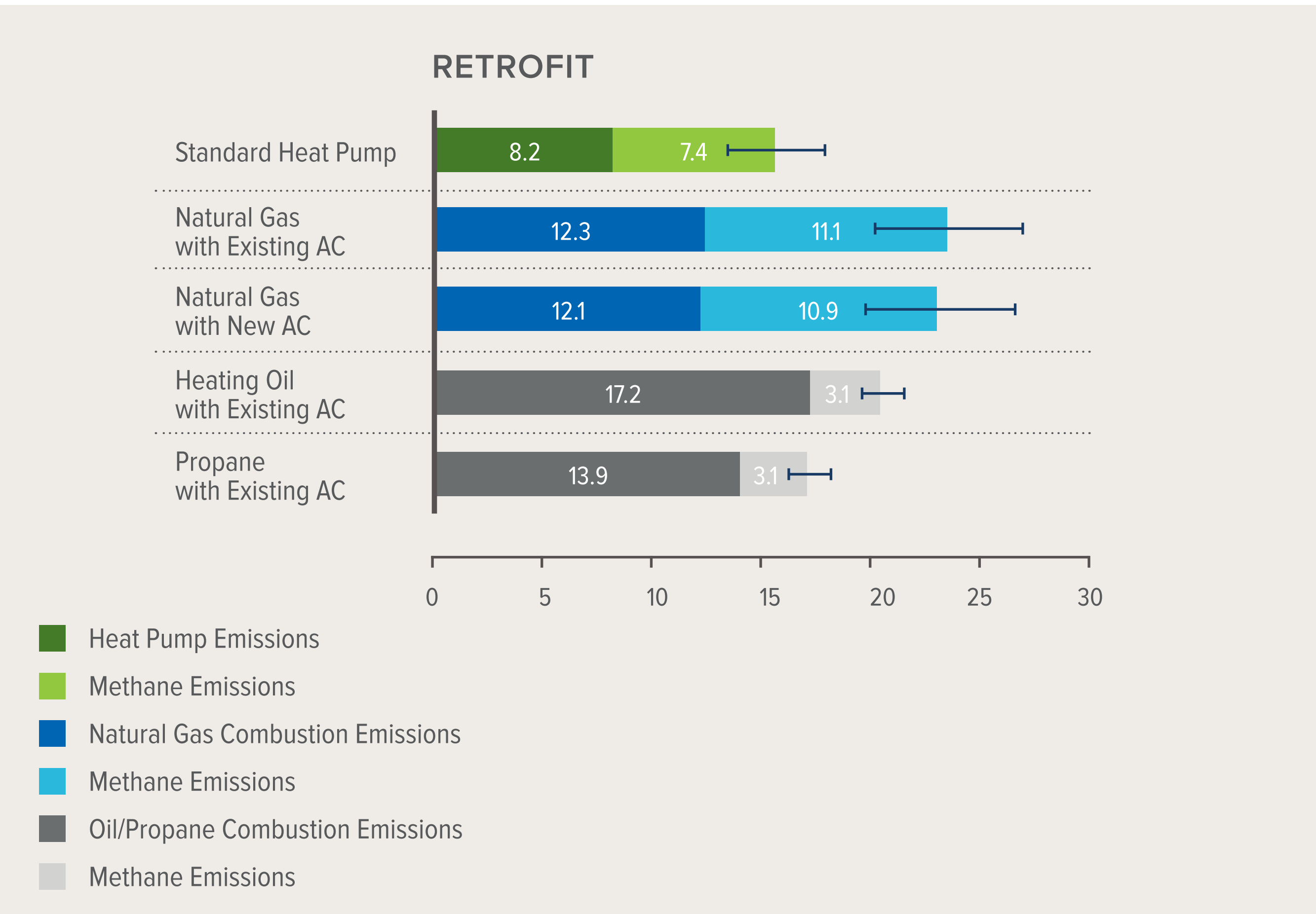


In other geographies, we conservatively assume that the marginal unit on the electric grid is entirely natural-gas fired, based on approximation of system emissions data. Because additional emissions from methane leakage are proportional to emissions from natural gas, incorporating methane leakage does not change which scenarios are more or less carbon intensive.

However, the carbon-intensive oil and propane systems used in the Northeast do not have methane leakage. When accounting for methane emissions in Providence, propane becomes slightly more attractive than natural gas. Heating oil, however, remains the most carbon-intensive fuel option, and heat pumps remain the least.

**FIGURE 13**

ANNUAL EMISSIONS OF HEATING IN PROVIDENCE RETROFIT WITH METHANE LEAKAGE (THOUSAND LB. $CO_2E$)



04

# A CLOSER LOOK: GEOGRAPHIES IN DETAIL

# A CLOSER LOOK: GEOGRAPHIES IN DETAIL

We assessed results in four cities: Oakland, California; Houston, Texas; Providence, Rhode Island; and Chicago, Illinois. In each geography, we compared the lifetime cost and carbon impacts of natural gas and heat pump systems in both new construction and retrofit homes. Because each geography is unique in terms of predominant fuel types, climate, and electricity rates, we considered additional scenarios for certain geographies. In Providence, we also compared heating oil and propane systems, as many homes in the Northeast use these fuels rather than natural gas. For time-varying rates in Oakland and Houston, we also compared flexible devices optimizing for energy costs in response to these rates.

In this section, we highlight the nuances of these different scenarios and offer some geographically specific recommendations and opportunities.

## RESULTS: OAKLAND, CA

In Oakland, heat pumps produce universally less carbon emissions compared to natural gas systems, and they are cost-effective in many scenarios.

For newly constructed buildings, heat pumps are universally more cost-effective, even without optimizing for demand flexibility, primarily because the

**FIGURE 14**

NET PRESENT COST OF WATER AND SPACE CONDITIONING, OAKLAND (THOUSAND $)

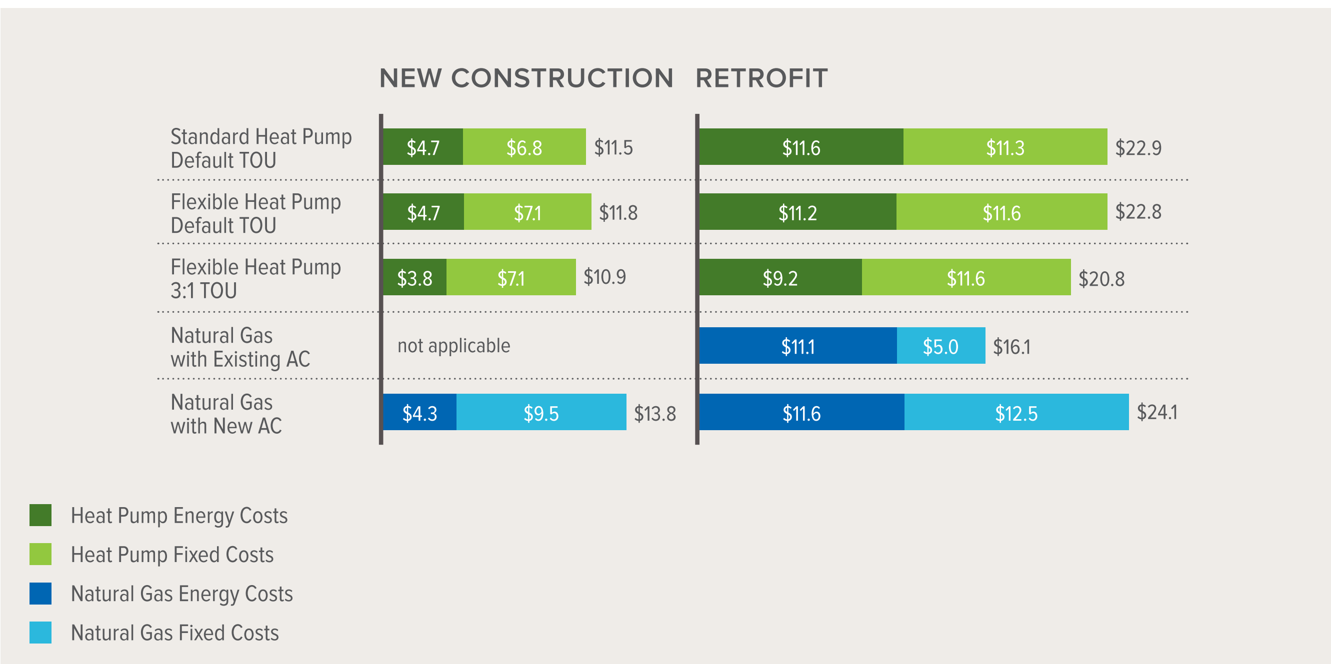
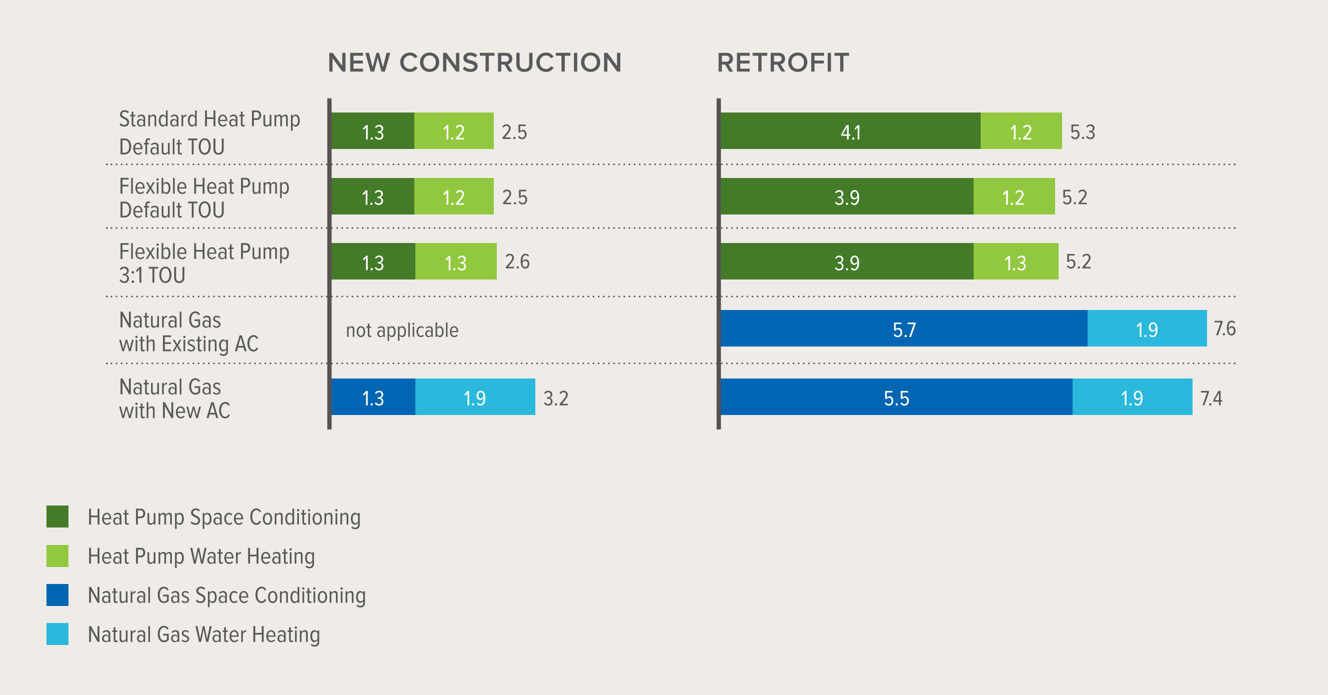


**FIGURE 15**

ANNUAL MARGINAL CARBON EMISSIONS IN OAKLAND (THOUSAND LB. $CO_2$)




heat pump provides both heating and air conditioning, avoiding the need to purchase both a furnace and an air conditioner. In Oakland, we consider two time-of-use rates. The default TOU represents the rate structure that most California residential customers will experience starting in 2019. Because nearly all customers will be enrolled on this TOU rate by default, we do not evaluate a flat electric rate. Because this default rate has relatively mild price differentials (only up to 20% price premium for peak periods), we also evaluated a representative 3:1 TOU rate as an illustrative example of a rate with increased price differentials, like some of PG&E's opt-in rates.[vi]

The flexible device on the 3:1 rate offers the most lifetime savings as it optimizes for demand flexibility by strategically preheating or precooling space and water, saving nearly $1,000 in lifetime energy costs compared to an inflexible device on the standard rate. The default TOU rate has too small a price differential (at most, peak pricing is 19% greater than off-peak pricing) to encourage significant load shifting or to capture significant savings, and it may not recoup the added cost of equipping the devices with extra control capability to operate flexibly.

In retrofit buildings, heat pumps are more expensive than simply replacing a gas furnace and water heater. While natural gas remains the cheapest option, optimizing for demand flexibility with a hypothetical 3:1 TOU rate makes a heat pump system more cost-effective, saving more than $2,000 over a standard,

[vi] The 3:1 TOU rate is a representative time-of-use rate where peak pricing is three times as expensive as off-peak pricing.

non-optimized heat pump. However, if a household is simultaneously replacing both an air conditioner and natural gas space and water heating systems, it is more cost-effective to electrify; rather than paying for an air conditioner, furnace, and water heater, households can purchase just two devices: an air-source heat pump and heat pump water heater. The flexible devices on the default TOU have a slightly higher cost than a standard device; the savings possible from demand flexibility are too small to overcome the increased device costs to enable demand flexibility.

Building electrification already reduces carbon in California with today's grid, and this carbon benefit will increase as California's grid continues to decarbonize. In all scenarios, heat pump systems produce significantly less carbon emissions than natural gas systems; retrofit households with heat pumps would emit 2,000 fewer pounds of carbon per year than natural gas systems. This is true even based on today's marginal generation mix, which averages about 1,000 lb. $CO_2$/MWh. As California's grid becomes increasingly renewable in response to the state's mandate for 50% renewable energy by 2030, the long-term impact of adding electricity demand will drive significant new renewable generation.

Notably, new construction homes have less than half the carbon footprint as the less-efficient existing home modeled here, even in Oakland's mild climate. This reinforces the importance of energy efficiency standards in new building, and of efficiency retrofits in existing buildings, regardless of fuel choice.

### Recommendations based on Oakland results

- Recognize and encourage all-electric new construction buildings as both a cost-reducing and carbon-reducing measure through new building codes and incentive programs.

- Limit or stop further expansion of the natural gas distribution system to service more homes. Electric space and water heating is likely to provide the same service to customers for less cost and carbon emissions, and avoid the risk of stranded gas distribution assets.

- Encourage load shifting of space and water heating loads into midday periods of high solar generation, to accommodate California's duck curve—the curve showing the difference in electricity demand and the amount of available solar energy throughout the day. The proposed default TOU rates have insufficient price differentials to encourage significant load shifting for thermal loads. Alternatives include opt-in rates with higher price differentials, utility demand response programs, or procurement of third-party aggregator solutions.

## RESULTS: HOUSTON, TX

For new construction, standard heat pumps offer more than $3,500 in lifetime savings as compared to natural gas space and watering heating with an air conditioning system. However, in retrofit buildings, natural gas systems remain cheaper than electrification by a similar margin. For a household facing replacement of both a gas furnace and air conditioning unit, heat pumps can offer significant lifetime savings, more than $2,000 as compared to replacing both devices individually.

Heat pump systems on TXU Energy's "Free Nights" rate, with higher electricity prices during the day and free electricity at nights, have higher costs than heat pumps on a flat rate plan, due to the significant daytime cooling load in Houston. However, for a customer who does use the Free Nights rate, optimizing heat pumps for demand flexibility saves around $1,000 in net present cost. This includes preheating water overnight and precooling or preheating the home aggressively while electricity is free to reduce consumption during the day.

Standard heat pumps do reduce carbon emissions compared to natural gas in Texas. Natural gas systems are 15% more carbon intensive than heat pump systems in new homes, and 10% more carbon intensive in retrofit homes.

Optimizing for Free Nights can lead to unintended consequences for carbon: flexible devices, optimized to preheat or precool very aggressively during the

**FIGURE 16**

NET PRESENT COST OF WATER AND SPACE CONDITIONING, HOUSTON (THOUSAND $)

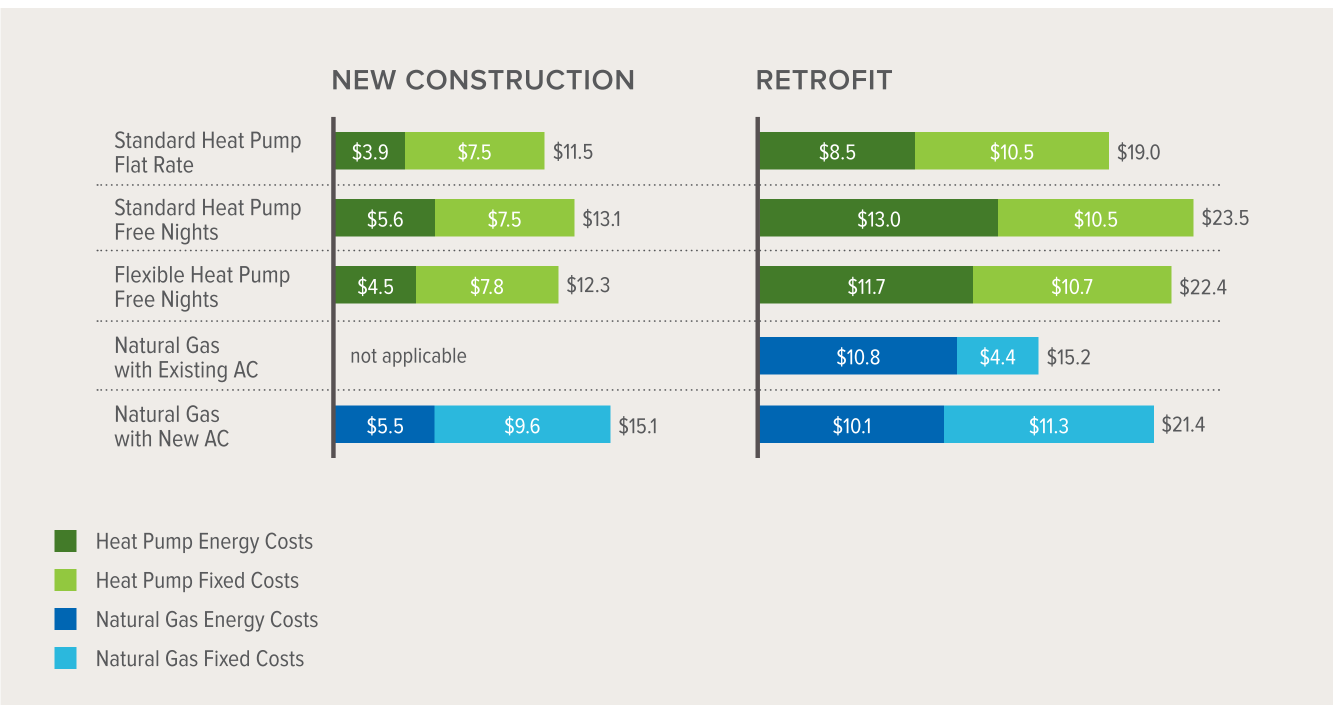
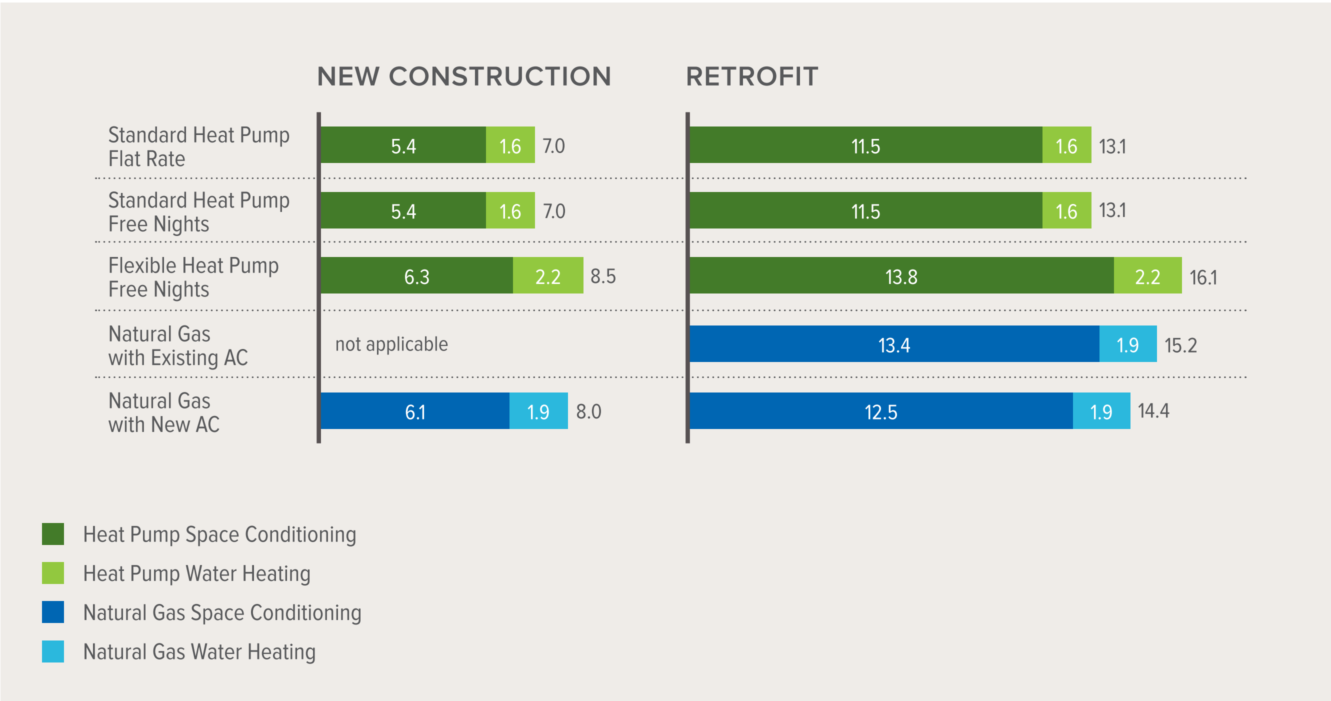


**FIGURE 17**

ANNUAL MARGINAL CARBON EMISSIONS IN HOUSTON (THOUSAND LB. $CO_2$)




night when electricity is free, use much more energy than standard heat pumps. This additional energy use increases emissions, making a flexible heat pump 20% more carbon intensive than a standard heat pump, and 12% more carbon intensive than a natural gas system for a retrofit building. Note that this conclusion applies to the short-term impact of increased nighttime energy use but does not consider the long-term impact of increased nighttime demand, and, for instance, the potential for accommodating more wind power on the Texas grid.

### Recommendations based on Houston results

- Retailers can offer new bundled electrification packages, including whole-home electrification and tailored rates or demand response programs for these customers. Sophisticated offerings could include smart thermostat programs to optimize preheating and precooling based on the market prices the retailer faces while keeping customer comfort within acceptable ranges. Innovative products for environmentally conscious customers could further optimize for integration of wind resources on Texas's grid.
- Combine building efficiency measures with electrification. As in other geographies, energy costs and carbon impacts for efficient new homes are less than half those in inefficient buildings.

## RESULTS: PROVIDENCE, RI

In Providence, heat pumps are more cost-effective and reduce carbon emissions in all scenarios, with the exception of retrofits of existing natural gas systems. Electrification offers particularly large carbon and cost savings potential compared to heating oil and propane systems.

For newly constructed homes, heat pumps are the most cost-effective option as compared to all fossil fuels, saving more than $2,000 against the next cheapest option, natural gas.

In existing homes, replacing a natural gas furnace and water heater with new gas devices costs less than a heat pump retrofit, regardless of whether a household is replacing an air conditioner simultaneously. The combination of Rhode Island's cold climate, which reduces the efficiency of heat pump heating performance, and a leaky home results in high electricity usage for heating a retrofit home. Combined with relatively high electricity prices in Rhode Island, this high heating usage makes electrification more costly than natural gas for retrofit homes.

However, many areas in New England lack gas infrastructure and instead rely on heating oil or propane; heat pumps have a lower net present cost than both heating oil- and propane-fired systems. Propane systems are extremely expensive, due to high fuel costs; switching to heat pump systems can

**FIGURE 18**

NET PRESENT COST OF WATER AND SPACE CONDITIONING, PROVIDENCE (THOUSAND $)

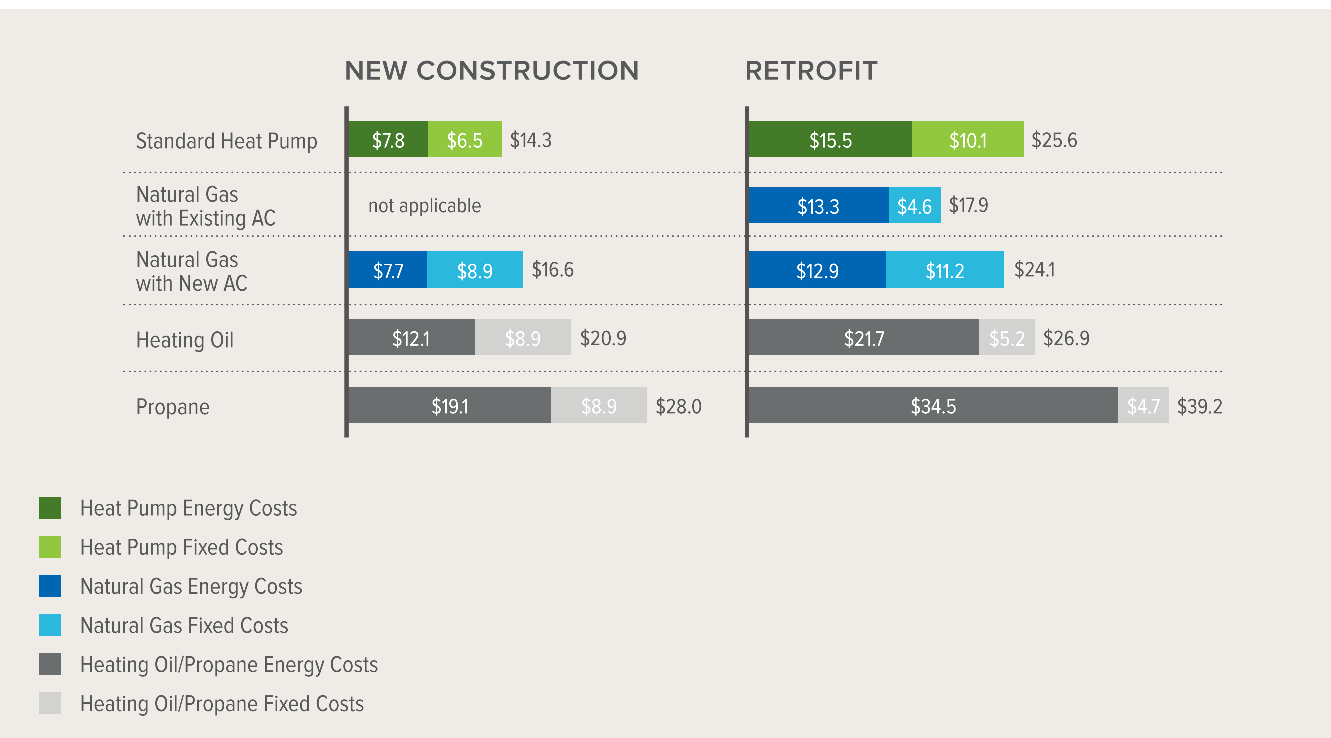
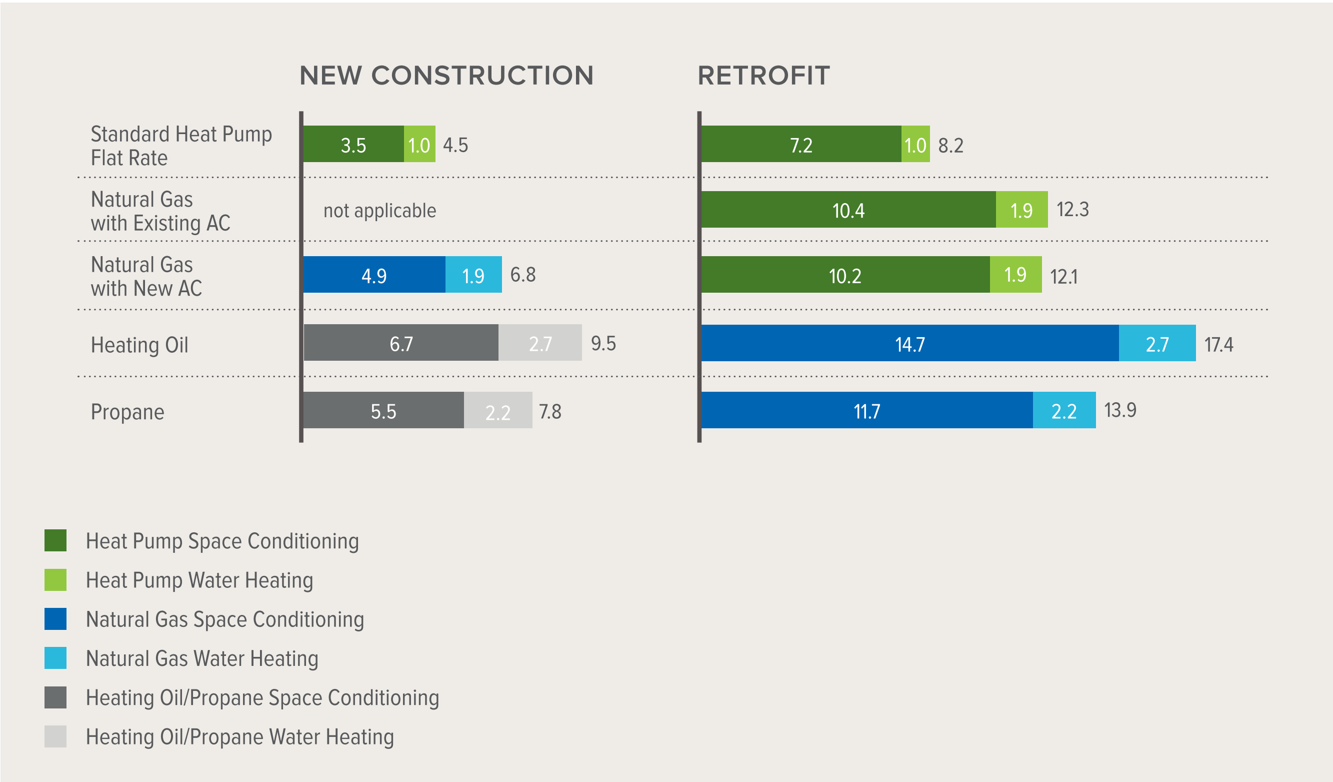


**FIGURE 19**

ANNUAL MARGINAL CARBON EMISSIONS IN PROVIDENCE (THOUSAND LB. $CO_2$)




save at least $10,000 in lifetime costs compared to propane. Where gas infrastructure does not currently exist, households can see significant savings from switching to electric heat pumps.

Given the low carbon intensity in Rhode Island—on average, the marginal emissions intensity is 815 lb./MWh—electrification of space and water heating significantly reduces emissions compared to gas, oil, or propane. Heating oil is particularly carbon intensive, and electrification cuts emissions in half for heating oil customers. Even natural gas systems produce about 50% more carbon emissions than heat pumps.

Given Rhode Island's commitment to reduce statewide greenhouse gas emissions 85% below 1990 levels by 2050 (and 50% by 2035), electrification of space and water heating will be a critical strategy to meet these targets.

For both new construction and retrofit, heat pumps produce significantly less emissions than all fossil fuels, given the low-carbon electricity mix in New England. Natural gas systems have the second lowest emissions, followed by propane, then heating oil. For both new construction and retrofit, heating-oil systems produce twice the carbon emissions as heat pumps. Natural gas systems produce 40% more carbon emissions than heat pumps in both newly constructed and retrofit buildings.

### Recommendations based on Providence results

- Prioritize electrification programs targeting customers currently using heating oil or propane in their homes, as electrification has the greatest immediate carbon and cost benefit for these customers. Specifically, prioritize electrification as a carbon- and cost-reducing measure rather than extension of natural gas service.

- Discontinue utility programs encouraging customers to switch to natural gas,[21] as these programs will not enable Rhode Island to meet its mandate for greenhouse gas reductions. In particular, scrutinize customer-facing language such as the following passage on one utility's website, which gives customers the false impression that natural gas is the cleanest option: "Natural gas is the cleanest-burning fossil fuel and a highly efficient form of energy. It has fewer impurities and reduces $CO_2$ emissions by 27%, so you'll feel good about helping the environment."[22]

## RESULTS: CHICAGO, IL

For newly constructed homes, heat pumps are significantly more cost-effective than installing both air conditioning and a gas furnace and water heater; a heat pump system will save $4,000 over the lifetime of the device.

In existing buildings, heat pump retrofits are more expensive than replacing natural gas furnaces and water heaters with new gas devices. However, compared to replacing both natural gas systems and air conditioners simultaneously, heat pumps are lower cost.

In the Chicago region of the PJM market, marginal generation on the grid is currently dominated by coal, meaning increases in load drive higher coal output today and thus additional short-term emissions. By this short-term marginal measure, heat pump systems have about 50% more carbon emissions than natural gas for both retrofit and new construction homes. This analysis used 2016 marginal emissions data. Since 2016, coal plant retirements and further development of renewable energy projects have continued to change the carbon intensity of the regional grid. For example, the 1,200 MW Pleasant Prairie coal plant just north of Chicago is slated for closure in 2018, as 350 MW of new solar generation is planned in the same region.[23]

### Recommendations based on Chicago results

- Continue to prioritize energy efficiency programs while laying the groundwork for customer electrification initiatives in anticipation of continued decarbonization of the regional grid. Given the expectation that substantial market development in building electrification will take several years, during which the continued pace of coal retirement will reduce grid emissions, utilities in the Chicago region should begin developing and introducing these programs now.

**FIGURE 20**

NET PRESENT COST OF WATER AND SPACE CONDITIONING, CHICAGO (THOUSAND $)

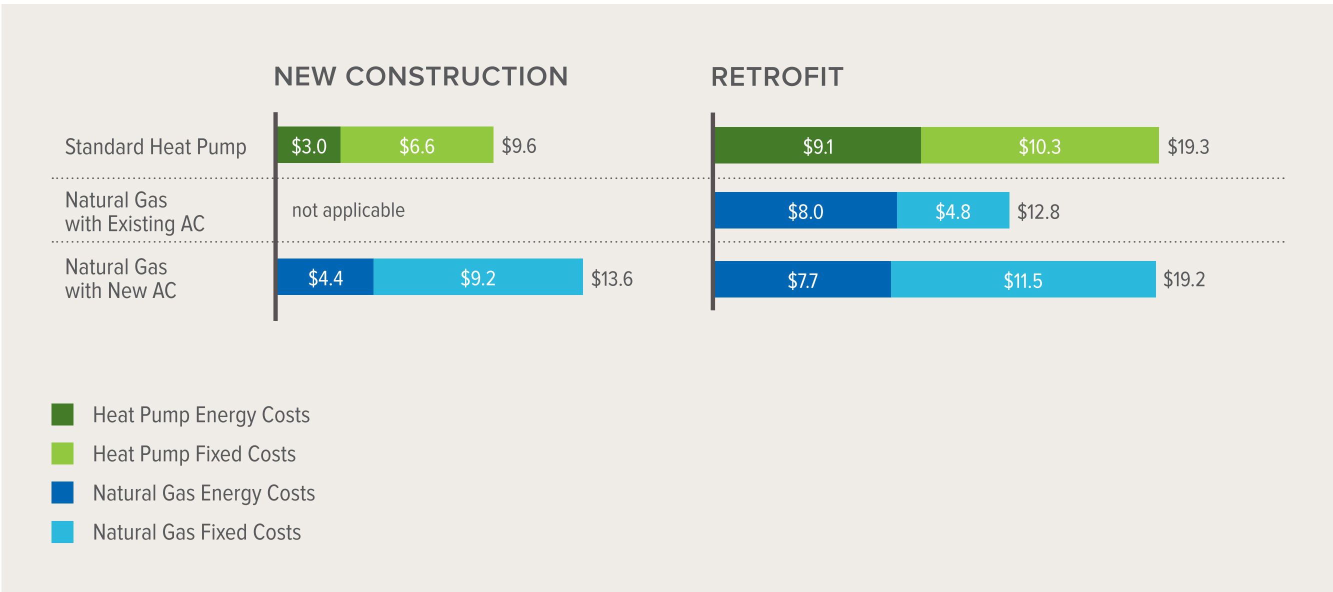
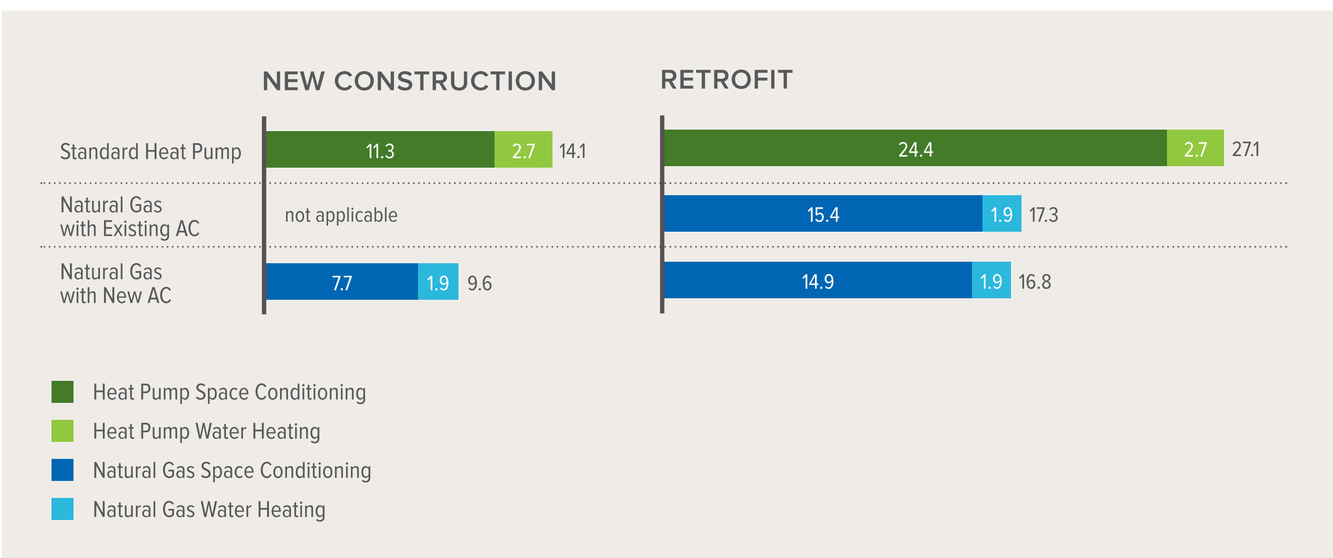



**FIGURE 21**

ANNUAL MARGINAL CARBON EMISSIONS IN CHICAGO (THOUSAND LB. $CO_2$)



## EVEN WHEN HEAT PUMPS DRAW POWER FROM NATURAL GAS POWER PLANTS, THEY REDUCE CARBON COMPARED TO BURNING GAS IN THE HOME

Across much of the US today, the marginal generator ramping up or down to meet new demand is often powered by natural gas, begging the question whether a natural gas plant powering an electric heat pump is actually more efficient than burning natural gas in the home for heat. Here we compare the annual greenhouse gas emissions of a natural gas-fired water heater with a heat pump water heater that sources its electricity from natural gas. Assuming a combined-cycle gas turbine, the greenhouse gas (GHG) emissions of the electric system are less than the gas-fired water heater. Electric resistance water heaters, which have historically dominated the electric water-heater market, have the highest emissions footprint on a gas-dominated grid. With today's technology, it is less efficient to burn gas in the home than to burn it at

**FIGURE 22**

COMPARISON OF FUEL CONSUMPTION AND GHG EMISSIONS FOR EXAMPLE WATER HEATING

| THERMAL ENERGY TO HEAT WATER (ANNUAL) | ENERGY INPUT TO WATER HEATER | ELECTRIC ENERGY GENERATED | NATURAL GAS CONSUMED | GHG EMISSIONS LBS $CO_2$ |
|---|---|---|---|---|
| 10.0 MMBtu 2,921 kWh | COP 0.62 Natural Gas 16.1 MMBtu | n/a | 16.1 MMBtu | 1,879 |
| 10.0 MMBtu 2,921 kWh | COP 0.99 Electric Resistance 2,951 kWh | 7% Line Loss 3,173 kWh | 25.0 MMBtu CCGT Heat Rate: 7,878 Btu/kWh | 2,923 |
| 10.0 MMBtu 2,921 kWh | COP 2.32 Heat Pump 1,259 kWh | 7% Line Loss 1,354 kWh | 10.7 MMBtu CCGT Heat Rate: 7,878 Btu/kWh | 1,247 |
| 10.0 MMBtu 2,921 kWh | COP 2.32 Heat Pump 1,259 kWh | 7% Line Loss 1,354 kWh | No Fuels | 0 |

a power plant and run the electricity to the house. An electricity grid with a higher renewables mix or more efficient generation will have even less emissions.

## SPACE AND WATER HEATING: ARE THEY CREATED EQUAL?

Throughout this report we evaluate scenarios that electrify both space and water heating, but they have distinct characteristics that could encourage electrification of one over the other. In addition to the fact that space heating is more energy-intensive and costly (five to eight times more expensive in Chicago, for instance), we describe four additional considerations surrounding the two end uses:

- **Water heaters are better at load shifting:** Water heaters can generally provide more load shifting than space heating, without impacting individual comfort. This is especially true when water can be preheated to very high temperatures (e.g., 150–160°F) and provide hot water to the user for many hours without the need for additional energy use. In our Houston Free Nights scenario, for instance, this strategy shifts the large majority of energy use to nighttime and reduces annual energy costs for water heating from $154 to $48. The same strategy for space heating provides only a few dollars per year of savings, as the building cannot be comfortably heated so high or cooled so low outside normal temperatures, and does not retain heat as well as a water tank.

- **Space heating is more sensitive to climate:** Space heating with air-source heat pumps is affected more by climate than water heating. While modern cold climate air-source heat pumps perform well at cold temperatures, they are less efficient and consume more energy in these environments. For instance, while the Mitsubishi device we model in Chicago and Providence is capable of providing substantial heat at outdoor temperatures as low as -13°F, the coefficient of performance at max capacity decreases from 3.5 (at 47°F) to 2.1 (at 17°F) to 1.4 (at -13°F). Geothermal heat pumps can perform better at these cold conditions, but are cost-prohibitive for many customers.

- **Electric space heating is less suitable in inefficient buildings:** Space heating is closely tied to the energy efficiency of the building. Our new construction scenarios use 55–67% less energy for heating existing, less efficient homes in the same climates. For relatively inefficient homes, especially in colder climates, bundling insulation and sealing measures will be particularly important to reduce energy from space heating and mitigate the need for costly upgrades to the electric grid to meet increased peak demand.

- **Combining space and water heating in a retrofit unlocks more savings than either alone:** Additional savings are possible from fully electrifying a home and discontinuing service from a gas utility. Many gas bills include a monthly fixed charge for maintaining service (our Chicago scenario includes a $33 per month fixed charge[24]), which can only be eliminated with full home electrification.

# 05 DEMAND FLEXIBILITY WITH ELECTRIC HEATING

# DEMAND FLEXIBILITY WITH ELECTRIC HEATING

Electric space and water heating loads can be optimized to support efficient operation of the electric grid by shifting loads into periods of low-cost and abundant renewable generation, reducing loads during periods of peak demand, and providing other grid support services at the bulk power and local levels. These demand flexibility services can be grouped into four categories:

- **Load shedding** is the reduction of energy demand during periods of high system cost or physical strain on the grid. For space and water heating, many of today's utility demand response programs rely on direct load control to disconnect devices from the grid during peak times, or to cycle devices on and off to reduce their aggregate demand. Load shedding is also known as curtailment.

- **Load shifting** is a deliberate change in the time that energy is consumed, without reducing the total energy provided. Space and water heating loads may be shifted earlier in time by preheating a building or a water tank in advance of a peak period, so the building mass or water can retain enough heat to meet customer comfort needs without additional energy demand during peak time.

- **Bulk power ancillary services** represent more specialized services that support grid operations. These can include frequency regulation, which is provided by electric resistance water heaters today; fast frequency response, requiring very fast disconnect of loads in response to frequency deviations;[vii] and contingency reserves, which can be provided by turning off resistance or heat pump devices on 10–30 minutes notice in response to an unexpected grid event.

- **Local ancillary services** include voltage management, hosting capacity expansion (e.g., by shifting more load into periods of local solar generation), or peak management specific to a distribution circuit. These local services have been deployed in limited cases so far, both in non-wires alternatives projects and in emergency peak management, but could be expanded with sophisticated distributed energy resources management or granular locational pricing.

In this report, we model strategies that combine load shifting (i.e., preheating or precooling ahead of peak periods) and load shedding (i.e., reducing a set point during peak periods) in response to time-of-use electric rates. This is a conservative approach to valuing demand flexibility, as we do not evaluate more granular or dynamic rate structures or the ability to provide ancillary services. We discuss below several approaches to increase the demand flexibility value of these devices, which with new and expanded compensation mechanisms, could further improve the economic value proposition of electrifying space and water heating.

As an illustration of the load shifting value from controllable water heating loads in supporting variable renewables, Figure 23 shows how a modeled customer's average daily load shape for a heat pump water heater changes when optimized for a time-of-use rate. In this example, the customer subscribes to Hawaiian Electric Company's residential time-of-use rate, with cheapest energy during the midday period when solar power is abundant, and most expensive during the system's evening peak. In regular operation without any demand flexibility, the water-heating load is spread throughout the day, with 29% falling during

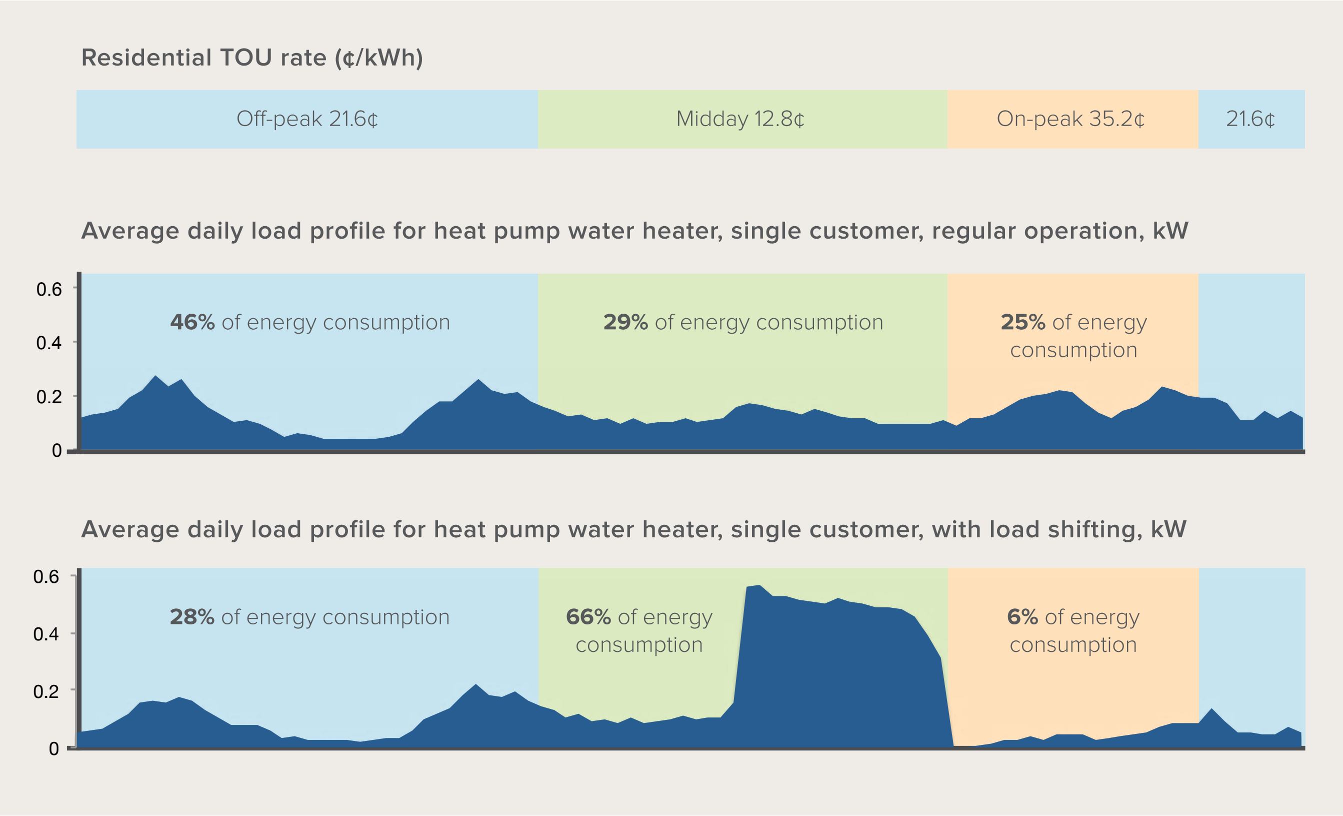
[vii] "Very fast" here refers to programs that can disconnect loads within as little as 0.2 seconds of a frequency deviation.

the midday period of abundant solar, and 25% during the expensive evening peak. When optimized for the time-of-use rate, however, the water heater preheats aggressively during the midday period, then reduces its set point in the evening period. As a result, two-thirds of the energy is consumed during midday, and only 6% during the expensive peak period. Although the load-shifting strategy consumes 10% more energy over the course of the year, the customer's energy bill is 20% lower than in the uncontrolled scenario.

Notably, this strategy relies on superheating water to much higher temperatures than typical (in this case, up to 150°F). To ensure consumer safety, this strategy requires installation of a thermostatic mixing valve to ensure water is delivered to the user at safe temperatures. Superheating strategies are already in use for demand response, for instance in the Great River Energy program in Minnesota, with 70,000 controlled water heaters.[26]

**FIGURE 23**

WATER HEATER LOAD SHIFTING FOR HAWAII TIME-OF-USE RATE



## APPROACHES BEYOND TIME-OF-USE OPTIMIZATION

In the scenarios we evaluated we found roughly $2,000 to $4,000 in demand flexibility value, on a 15-year discounted cash flow basis, when optimizing for time-of-use rates with significant peak to off-peak price differentials (i.e., Oakland 3:1 TOU and Houston Free Nights). While these cases certainly offered greater value than those with milder price differentials, they do not fully capture the value demand flexibility could provide with electrified space and water heating. More value could be captured either through improved rate design or expanded demand response programs.

### IMPROVED RATE DESIGN

Additional rate elements could enable more value from flexible space and water heating, including critical peak pricing, more granular time periods, and more dynamic pricing:

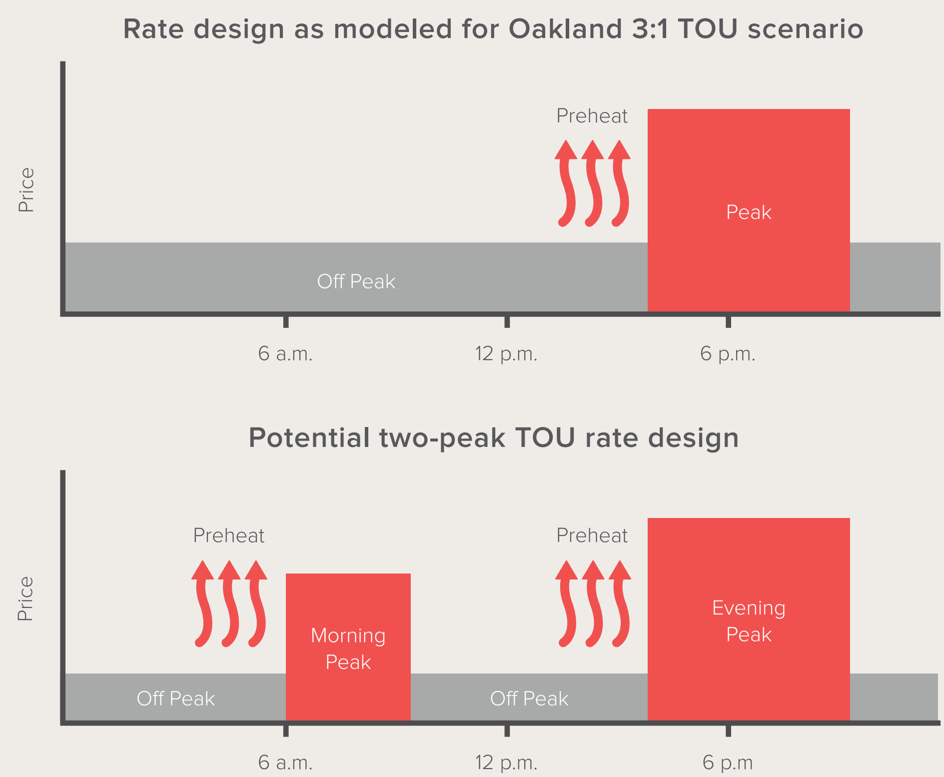
- **Critical peak pricing** provides very high electricity prices during a limited number of annual events of several hours' duration. In return, the customer's electricity rates are reduced by a few percent all other hours of the year or season. With pre-conditioning and curtailment strategies, electric water heating and space heating and cooling can minimize demand during critical peak periods and reap the benefits of reduced year-round pricing.

- **More granular time periods** can allow more frequent use of pre-conditioning strategies and further reduce the effective price of electricity for heating and cooling. As shown in Figure 24 below, our Oakland 3:1 TOU scenario preheats water once per weekday, before the peak period begins at 4 p.m. However, the California electric system commonly experiences two peak demand periods per day, a morning peak and evening peak, as well as a midday slump in net demand as solar generation meets a significant portion of system needs. A customer facing multiple peak-off-peak cycles per day could take advantage of more opportunities to preheat during low-cost off-peak periods, and more peak pricing periods could result in lower off-peak pricing. Some rates vary in price hourly or, in extreme cases, minute by minute.

- **More dynamic pricing** offers the customer prices that closely reflect the changing needs of the electric system. Real-time pricing and other dynamic pricing schemes can introduce greater volatility and allow sophisticated device controls to maximize use of energy during low-priced periods. For instance, RMI's most recent demand flexibility report showed how water heaters could evaluate market conditions over the coming 12 hours and dynamically replan its heating schedule to take advantage of low-cost periods.[27] For maximum benefit, these rates should assign time-varying value to distribution and transmission costs as well as energy, or they risk diluting the variation in the price signal.

**FIGURE 24**

CREATING MORE GRANULAR TIME PERIODS WOULD ALLOW MORE FREQUENT APPLICATION OF LOAD-SHIFT STRATEGIES




In the near term, these rate design principles may show up in more utility-designed rates. Ultimately, the same principles may manifest in sophisticated transactive energy market structures that offer dynamic, granular, and location-specific pricing reflecting grid needs, customer preferences, and market conditions. The Retail Automated Transactive Energy System (RATES) pilot project in southern California is an early example of such a system, with automated controls optimizing a customer's energy use as spot prices for electricity change dynamically.[28]

## DEMAND RESPONSE PROGRAMS

These programs provide centralized control of distributed devices, and may be run by a utility or a third-party aggregator. Their advantage over time-of-use rates is the ability for the aggregator to optimize across multiple value streams based on dynamic grid needs on a highly granular basis in both time and location, without overburdening the customer with complex pricing. Notably, these are starting to expand in scope from traditional utility air conditioning and water-heating demand response programs, which

are often limited to one-way communication to curtail load during peak periods. Enhanced value can also come from value stacking across multiple services, from meeting location-specific grid needs, and from ancillary service provision.

- **Value stacking:** Centrally managed programs can optimize device usage across several value streams. Green Mountain Power's eWater program provides a helpful example. The utility prioritizes among several actions based on greatest system value. During annual ISO New England peak events, water heaters are curtailed to minimize generation capacity costs. During monthly peaks within Green Mountain Power's service territory, devices are again curtailed to minimize transmission capacity charges. On other days, energy is shifted from high-price periods to low-price periods to reduce variable energy costs. Finally, the utility can bid these aggregated demand resources into the ISO market for products such as frequency regulation or contingency reserves for additional value.

- **Location-specific services:** Demand flexibility can support deferral of location-specific infrastructure upgrades, or provide other services such as increasing hosting capacity for distributed solar by building midday load on saturated circuits.

- **Ancillary services:** Electric space and water heating can also provide valuable ancillary services, either by participating in wholesale markets or by providing them directly to meet utility needs. Traditional electric resistance water heaters already provide frequency regulation to the PJM market through third-party aggregators. In aggregation, heat pump devices could provide this same service, though at smaller scale. They could also offer other products such as contingency reserves. Hawaiian Electric's recently approved demand response programs offer a notable example, with contingency reserves valued at $6 per kW per month, equivalent to up to $80 per year for space and water heating in our residential scenarios.

Across all of these rate design and load control options, we can expect the inherent value of demand flexibility to increase in the future, as power systems increasingly rely on variable renewable energy and net energy demand becomes more variable hour to hour and day to day.

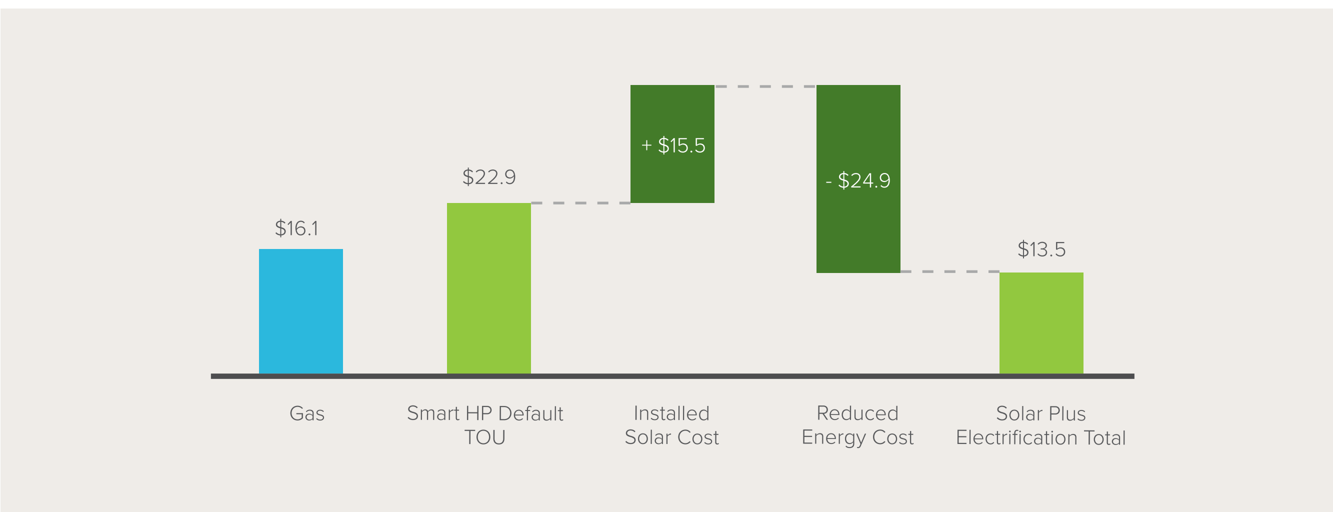
## COST-COMPETITIVE SOLAR PLUS ELECTRIFICATION IN CALIFORNIA

Customers who bundle solar with electrification can increase their energy savings and generate solar power to match their additional electricity consumption. We modeled rooftop solar as an addition to our Oakland retrofit default TOU scenario and found that solar plus electrification lowers net present cost below that of either a natural gas retrofit or electrification alone, though it increases initial capital cost.

We found a 6.5 kW solar system optimal for this customer profile, offsetting approximately 90% of the annual whole home electricity demand. This would add more than $15,000 in up-front costs for the solar installation, but reduce energy costs from $2,900 to $170 on an annual basis, or by almost $25,000 over 15 years on a discounted cash flow basis. Notably, we found that offsetting around 90% of energy consumption was more cost-effective than offsetting 100%, as PG&E's minimum monthly bills negate the benefit of offsetting the last 10% of energy consumption. California's shift to net energy metering by time-of-use period had only a minor effect, as the price differential between peak and off-peak periods is only 19% during summer and 5% the remainder of the year. Although the large up-front cost poses an additional barrier, packaging electrification with a solar installation may allow customers to take advantage of widespread financing mechanisms for rooftop solar, which could readily be expanded to cover electrification costs as well. Solar customers facing potential reductions in credit for exported energy may also find electrification maintains the value of their solar array by enabling more self-consumption of solar power.

**FIGURE 25**

NET PRESENT COST OF SOLAR PLUS ELECTRIFICATION COMPARED WITH GAS AND ELECTRIC FOR OAKLAND DEFAULT TIME-OF-USE SCENARIO (THOUSAND $)



## ELECTRIFICATION IS MORE COST-EFFECTIVE THAN EXPANDING GAS INFRASTRUCTURE TO MORE HOMES

Extending gas service to more homes is expensive. These costs can vary widely depending on a building's proximity to existing gas mains and other factors. We compiled utility-provided cost data from regulatory filings or customer quotes in 12 cases across five states, ranging from $1,000 to more than $24,000 per single-family home, with a median value of $8,800.

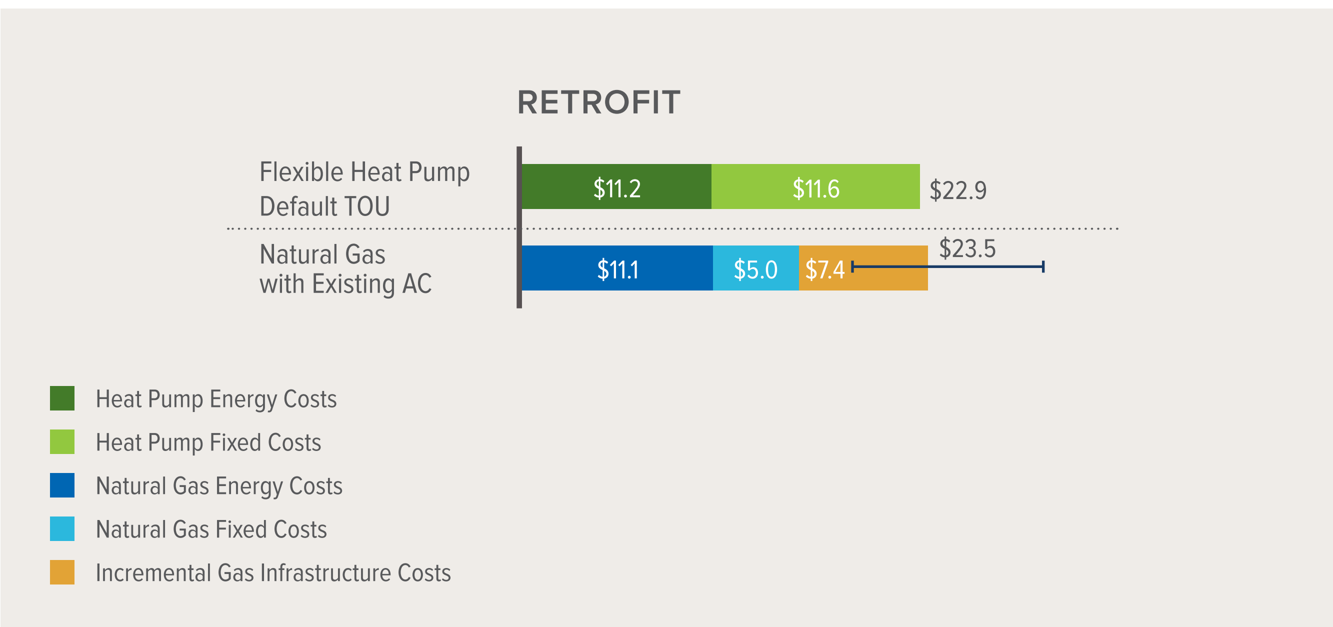
In Figure 26 we include this cost in comparing two Oakland retrofit scenarios: natural gas and electrification with default TOU for a home that does not already have gas service, showing that the heat pump scenario becomes more cost-effective than natural gas expansion.

Note that a portion of the gas distribution cost is covered by the customer's gas bill payments (45% of gas bills, or $1,400 over 15 years based on PG&E's 2016 revenue requirement[29]), so we only show the incremental cost above this amount: $7,400. In the electrification scenario, there may be additional electric distribution infrastructure costs not shown here.

While customer-specific factors will vary, we expect in most cases that heating electrification will cost less than extending gas service to homes not yet served

**FIGURE 26**

NET PRESENT COST OF OAKLAND RETROFIT GAS AND ELECTRIFICATION SCENARIOS WITH GAS INFRASTRUCTURE COSTS (THOUSAND $). ERROR BAR SHOWS 25TH AND 75TH PERCENTILE OF ESTIMATED GAS MAIN AND SERVICE COSTS




by gas, and that electrification of newly constructed homes will become even more attractive when developers and ratepayers can avoid the cost of gas mains and services.

## COST CHANGES NEEDED FOR COST-EFFECTIVE BUILDING ELECTRIFICATION RETROFITS

As shown above, in many retrofit scenarios for a home with existing natural gas space and water heating, switching to electric heat pump devices is more expensive today than retrofitting with a new gas furnace and water heater. A notable exception is the customer needing to replace both his furnace and air conditioner, which can be replaced with a single heat pump that performs both functions. But for the majority of homes currently using gas, changes to today's costs will be needed to make widespread electrification the low-cost option. Just as the solar industry has made progress reducing soft costs in solar energy installations, cost reductions in electrification will need to extend beyond appliance costs to include permitting, installation, financing, and customer acquisition. Several such changes could emerge, depending on the scale of market growth for heat pumps and many other unpredictable factors:

- **Device and installation costs are likely to decline:** Heat pump water heaters make up less than 1% of water heater sales today,[30] and their unsubsidized purchase prices are two or more times those of natural gas water heaters. Given the current immaturity of the market for these products, and the potential for significant economies of scale with increasing market share, their costs are likely to decline in the future. The National Renewable Energy Laboratory's (NREL's) *Electrification Futures Study* projects cost declines of 20–38% for air-source heat pumps and 42–48% for heat pump water heaters by 2050.[31] Likewise, in regions where contractors are currently unfamiliar with heat pump products, increasing scale and familiarity may reduce installation costs in the future.

- **The value of demand flexibility is likely to increase:** As variable renewable energy continues to grow, electricity markets will be more likely to experience large price differentials across seasons and times of day, including more periods of near-zero or negative wholesale pricing. This will inherently increase the value of flexible demand, and increase the value available to customers with flexible electric space and water heating.

- **Carbon pricing may expand and rise:** California is currently the only state where carbon pricing is applied to distributed natural gas, at a value around $15/ton.[32] At this value, a California gas customer is paying $14 extra per year in energy bills compared to an electric heat pump customer. As the statewide emissions cap declines in the future, and as the decarbonization of California's electric grid increases the carbon advantage of heat pumps over natural gas, these factors together will improve the cost-effectiveness of electrification. Other states may launch new carbon-pricing schemes that include distributed fuels, shifting the cost equation in other parts of the country.

- **Natural gas prices may rise:** Residential gas commodity prices are unpredictable and have remained relatively stable since 2010,[33] so we make no prediction of rising gas prices, but higher prices would improve the cost-effectiveness of electrification.

# 06 RECOMMENDATIONS FOR UTILITIES, REGULATORS, AND POLICYMAKERS

# RECOMMENDATIONS FOR UTILITIES, REGULATORS, AND POLICYMAKERS

Electrification of space and water heating presents a viable pathway to deep decarbonization, reduces carbon emissions in all but the most coal-dominated regions, can support renewable energy integration with the proper control strategies, and costs less than fossil fuel alternatives in a significant portion of scenarios. However, most of the 56 million American households currently heated with natural gas will not find it cost-effective to switch to electric heat pumps at today's prices. To capture the near-term benefits of fuel switching in the most advantageous scenarios, and to prepare for a long-term approach that includes widespread cost-effective electrification, we offer five immediate recommendations for regulators, policymakers, and utilities:

1. Prioritize rapid electrification of buildings currently using propane and heating oil in space and water heating

2. Stop supporting the expansion of the natural gas distribution system, including for new construction

3. Bundle demand flexibility and energy efficiency programs with electrification initiatives

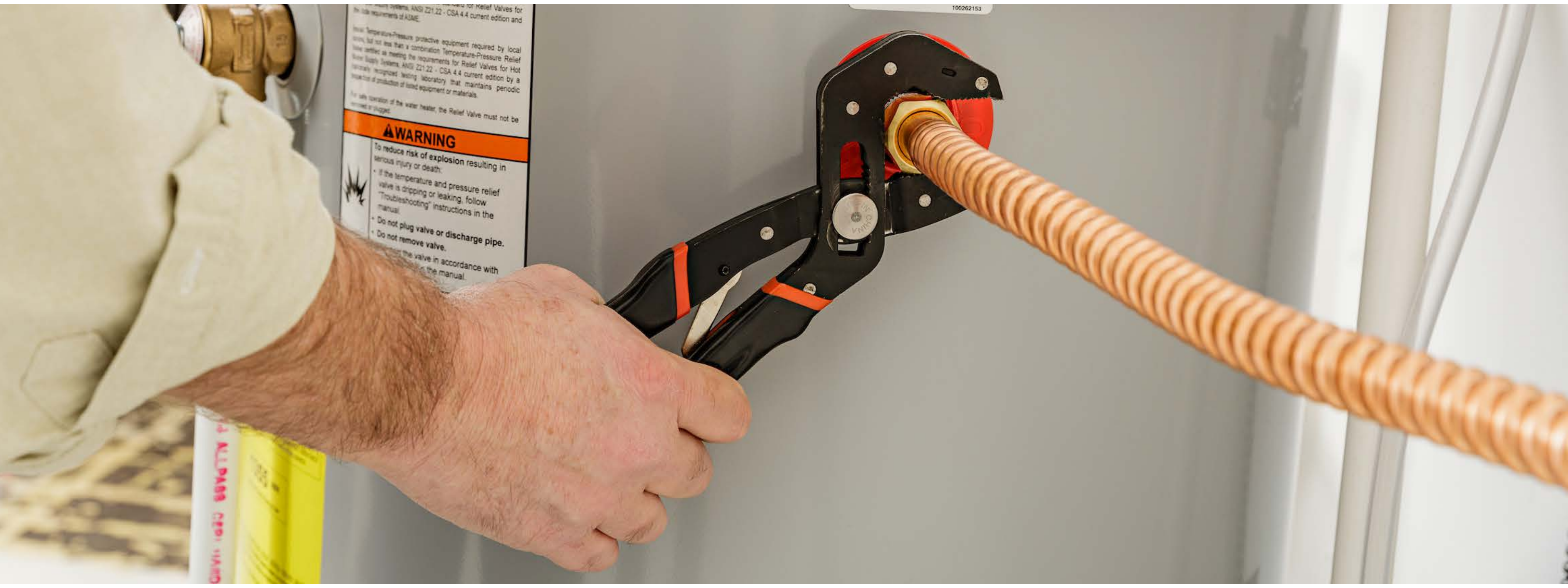
4. Expand demand flexibility options for existing electric space and water heating loads

5. Update energy efficiency resource standards and related goals to account for total energy reduction across fuels

## RECOMMENDATION 1: PRIORITIZE RAPID ELECTRIFICATION OF BUILDINGS CURRENTLY USING PROPANE AND HEATING OIL IN SPACE AND WATER HEATING

### RATIONALE

Electrification of homes using propane and heating oil for space and water heating already reduces carbon emissions and costs less (than propane) or the same (as oil). These fuels are more carbon-intensive and more expensive than either natural gas or electric



heat pumps. These homes typically do not have existing natural gas service, and switching customers to electricity is more cost-effective than extending gas mains and services to more customers. And although less than 10% of homes heat with propane or heating oil,[34] these fuels account for more than 20% of residential fossil fuel carbon emissions.[35]

### RECOMMENDED ACTIONS:

- Prioritize energy efficiency incentives and targeted utility programs that displace consumption of propane and heating oil with efficient electric heat pumps.
- Make electrification easier for customers by promoting it through utility marketing, developing a qualified contractor network for simple installation experience, providing standard financing offers, and structuring rebates so customers receive them at point of sale.
- Promote policy actions such as the Tier III Energy Transformation requirement in Vermont's Renewable Energy Standard,[36] which requires utilities to implement carbon-reducing projects such as electrification for customers, or Massachusetts' integration of heat pumps and other "renewable thermal" technologies into its Alternative Portfolio Standard.[37]

## RECOMMENDATION 2: STOP SUPPORTING THE EXPANSION OF THE NATURAL GAS DISTRIBUTION SYSTEM, INCLUDING FOR NEW CONSTRUCTION

### RATIONALE

Continued expansion of the natural gas distribution system is incompatible with the imperative to decarbonize buildings' energy use. Fourteen states currently have official targets of greater than 75% reductions in greenhouse gas emissions by mid-century,[38] and achieving these goals will require discontinuing the large majority of natural gas use in buildings. This means that many or all gas mains and services built today will cease to be used and useful by 2050 at the latest and will become stranded assets. This stranded asset risk alone should give regulators pause in their approval of continued ratepayer-funded investment in gas system expansion.

Many utilities—including the two largest in New England—prominently advertise to customers the option to switch to natural gas as a clean and cost-effective option without stating that electrification can be cleaner and more cost-effective.[39] State energy strategies may promote gas expansion, even while acknowledging the long-term need for building electrification. Connecticut's 2018 Comprehensive Energy Strategy does just this, simultaneously touting as an example of progress that the state "converted 39,104 residential customers to natural gas for heating" and stating that "to achieve the vision of a zero-carbon economy, widespread electrification of building thermal loads and the transportation sector is required."[40]

As shown in this report, electrification of homes, whether new construction or existing but not currently served by gas, is more cost-effective than extending gas service to these homes, installing gas furnaces and water heaters, and consuming gas to fuel them over their lifetimes, and already reduces carbon emissions in all but the most coal-intensive grids.

An ongoing California proceeding offers an immediate example. The state is considering funding gas service extension to disadvantaged communities in the San Joaquin Valley currently served by propane at high cost.[41] Pilot projects under this proceeding will compare the costs of whole home electrification to costs of gas service extension, including appliance upgrades. Initial utility cost estimates for gas expansion significantly exceed the typical utility allowance for such projects of around $2,000 per household.[42] Given California's commitment to 80% reduction in greenhouse gas emissions by 2050, consideration of public funding for gas expansion should acknowledge that achieving the state's climate goals would require foregoing use of this gas infrastructure by 2050 in favor of all-electric solutions.

### RECOMMENDED ACTIONS:

- Public utilities commissions can reexamine the methodology by which they determine utilities' allowance for costs of gas expansion. Typically, utility ratepayers fund the cost of gas system expansion up to a predetermined allowance, above which the developer (of new homes) or customer (of existing homes) must pay additional construction costs. These allowances are calculated as the net present value of distribution costs paid through customer rates over long time periods (e.g., 60 years in California,[43] 40 years in Pennsylvania[44]). Regulators should reconsider whether such long time horizons are appropriate given the risk of stranded assets.

- State energy offices can cease support for continued gas system expansion in their energy strategies and instead prioritize measures for building electrification.

- Cities can phase in all-electric, net-zero energy requirements for new construction, as described in RMI's *The Carbon-Free City Handbook*.[45]

- Regulators and policymakers considering new ratepayer-funded gas expansion to underserved communities should evaluate all-electric solutions carefully in comparison with gas options, acknowledging that new gas infrastructure bears significant stranded asset risk associated with the need to meet climate goals.

## RECOMMENDATION 3: BUNDLE DEMAND FLEXIBILITY PROGRAMS, NEW RATE DESIGNS, AND ENERGY EFFICIENCY WITH ELECTRIFICATION INITIATIVES

### RATIONALE

Widespread electrification will add substantial new load to the electricity system, and if not well managed could eventually impose large costs on the electricity system at both the bulk and local levels. Demand flexibility can shift load from high-cost to low-cost times, minimize contribution to system peak (especially in winter), and help cost-effectively integrate high penetrations of variable renewable energy. The value of this demand flexibility to the system will increase in the future, as growing renewable generation introduces more extended periods of zero or negative marginal pricing in electricity markets, while increasing the need for fast-ramping resources to balance the system. Energy efficiency can substantially reduce the total energy use and peak demand, especially for space heating. The efficient new construction buildings modeled in our analysis consume roughly half the energy for space heating as the existing buildings in the same cities.

### RECOMMENDED ACTIONS:

- Utilities can bundle electrification initiatives with new demand flexibility customer programs. Green Mountain Power's eControl offer provides a notable example, as a free connected add-on to ductless heat pumps that offers the utility the ability to shift or curtail demand when needed.[46] This product can be offered in concert with GMP's utility-run ductless heat pump program.

- Likewise, utilities or contractors providing electrification retrofits to customers should evaluate home energy performance and offer efficiency upgrades at the same time, to reduce the size and cost of heat pump needed and to reduce energy demand and cost.

- Expand utility rebate programs for air conditioning to offer incentives for customers replacing traditional air conditioning units with efficient heat pump units for both cooling and heating.

- Expand time-varying rates to more customers, and ensure they offer a meaningful price differential that will actually result in load shifting. Note that programs like the California utilities' proposed default time-of-use rates offer price differentials that are too small to offer meaningful value from load shifting thermal loads, as shown in the body of this report.

- Default all or a portion of customers onto these time-varying rates. This could mean all customers, all participants in an electrification program, all new customers, or some other subset. Using time-varying rates as a default option will ensure they reach many more customers than opt-in approaches.


## RECOMMENDATION 4: EXPAND DEMAND FLEXIBILITY OPTIONS FOR EXISTING ELECTRIC SPACE AND WATER HEATING LOADS

### RATIONALE

There are more than 50 million electric water heaters currently installed in the US,[47] and only 1% of those participate in demand response programs.[48] Likewise, the more than three million customers enrolled in either air conditioner switch or thermostat demand response programs (mostly for air conditioning rather than heating)[49] is small in comparison to the 43 million homes using electric space heating.[50]

These devices, especially the higher-powered resistance devices, can offer the same peak management and renewables integration benefits described above for heat pumps, at even higher value per device (because they consume more energy in the first place). Additionally, electric resistance water heaters are particularly adept at providing sophisticated grid services like frequency regulation, as in PJM where aggregated water heaters provided an average of more than 100 MW of regulation in 2017.[51]

### RECOMMENDED ACTIONS:

- Remove barriers to aggregated demand-side resource participation in wholesale market products, including energy, capacity, and ancillary services. These barriers include prohibitions on aggregated demand-side resource participation in some products and large minimum resource size requirements for individual loads or aggregations. The Federal Energy Regulatory Commission (FERC) is currently considering action to remove such barriers by requiring markets it regulates to allow aggregated resources to participate alongside traditional resources.[52]

- Expand utility demand response programs to cover more end uses and provide more services with each load. Many utilities lack water-heater demand response offerings, or smart thermostat programs that can address both heating and cooling. Utilities can also take a "value stacking" approach to dispatching enrolled resources for maximum value, optimizing value across generation, transmission, and distribution capacity; energy arbitrage; and ancillary services.

- Expand time-varying rates to more customers through default time-of-use rates or other rate designs that include significant price differentiation across time.

## RECOMMENDATION 5: UPDATE ENERGY EFFICIENCY RESOURCE STANDARDS AND RELATED GOALS TO ACCOUNT FOR TOTAL ENERGY REDUCTION ACROSS FUELS

### RATIONALE

Regulators, policymakers, and utilities will need to make adjustments to energy efficiency programs and targets in order to accommodate beneficial electrification. Energy efficiency programs have traditionally focused separately on reducing electric energy consumption (in kWh) and natural gas energy consumption (in therms).[53] This approach risks providing a disincentive to beneficial fuel switching, either for buildings or transportation, if a utility will be penalized for adding kWh of electric consumption to the system. Rather, energy efficiency targets should either be measured on a total energy basis—combining electricity, natural gas, and other fuels—or on the basis of total emissions associated with the energy consumption, as articulated in the 2016 *Electricity Journal* article "Environmentally Beneficial Electrification: The Dawn of 'Emissions Efficiency.'"[54] Otherwise, successful electrification could penalize utilities for not reducing electricity demand, even when it provides cost and carbon benefits. Additionally, policies that prohibit utilities from promoting fuel switching should be reevaluated to consider the benefits electrification could provide in meeting policy goals, including carbon reduction.

### RECOMMENDED ACTIONS:

- Update energy efficiency resource standards to allow utilities to meet their obligations with beneficial electrification that reduces total energy consumption or total emissions.

- Amend restrictions that prevent utilities from promoting beneficial electrification, particularly when it supports state policy objectives.

# 07 CONCLUSION

# CONCLUSION

Ultimately, reaching decarbonization goals will require displacing a significant amount of the existing natural gas use that heats space and water in buildings. Our analysis shows that replacing natural gas furnaces and water heaters with electric heat pump devices is often not cost-effective at today's costs. While some proposed concepts offer notable exceptions—such as "non-pipes alternatives" projects that redirect funds from planned gas main and service replacement to instead electrify the buildings served by the relevant gas main—widespread electrification will require some combination of additional cost reductions or increased value proposition to customers. These may include:

- Reduction in price of heat pumps, which is expected through greater economies of scale as the market for these products grows. NREL estimates these price declines will range from 20–38% for air-source heat pumps and 42–48% for heat pump water heaters by 2050[55]

- Reduction in contractor price for heat pump installation, which could occur as contractors become more familiar with newer heat pump devices, or as utilities or other entities develop bulk purchasing agreements with contractor networks

- Increasing future value of demand flexibility, as high penetrations of variable renewables create wider daily spreads in energy prices, and markets and pricing evolve to empower customers to capture more of this value

- Increasing applicability of carbon pricing (and higher carbon prices) applied to distributed fuels like natural gas (currently only existing in California)

- Increases in natural gas prices

These long-term developments, supported by near-term actions such as rapid electrification of propane and heating oil uses, cessation of the natural gas distribution system's expansion, and widespread participation of electric thermal loads in demand flexibility programs or time-varying pricing, can all advance a future in which buildings are completely powered by carbon-free energy and actively help balance a highly renewable, efficient, and affordable electric power system.

AP

# APPENDIX: METHODOLOGY

# APPENDIX: METHODOLOGY

## SCENARIOS

| GEOGRAPHY | SPACE AND WATER HEATING FUEL | RETROFIT SCENARIOS | NEW CONSTRUCTION SCENARIOS |
|---|---|---|---|
| CHICAGO, IL | **Electricity** | Standard heat pump on a flat rate | Standard heat pump on a flat rate |
| | **Natural gas** | Gas with new air conditioner<br>Gas with existing air conditioner | Gas with new air conditioner |
| HOUSTON, TX | **Electricity** | Standard heat pump on a flat rate<br>Standard heat pump on “Free Nights”<br>Flexible heat pump on “Free Nights” | Standard heat pump on a flat rate<br>Standard heat pump on “Free Nights”<br>Flexible heat pump on “Free Nights” |
| | **Natural gas** | Gas with new air conditioner<br>Gas with existing air conditioner | Gas with new air conditioner |
| OAKLAND, CA | **Electricity** | Standard heat pump on default TOU rate<br>Flexible heat pump on default TOU rate<br>Flexible heat pump on 3:1 TOU rate | Standard heat pump on default TOU rate<br>Flexible heat pump on default TOU rate<br>Flexible heat pump on 3:1 TOU rate |
| | **Natural gas** | Gas with new air conditioner<br>Gas with existing air conditioner | Gas with new air conditioner |
| PROVIDENCE, RI | **Electricity** | Standard heat pump on a flat rate | Standard heat pump on a flat rate |
| | **Natural gas** | Gas with new air conditioner<br>Gas with existing air conditioner | Gas with new air conditioner |
| | **Propane** | Propane with new air conditioner<br>Propane with existing air conditioner | Propane with new air conditioner |
| | **Heating oil** | Oil with new air conditioner<br>Oil with existing air conditioner | Oil with new air conditioner |

We model air-source heat pumps as the electrification option. "Standard devices" are air-source heat pumps for space conditioning and water heating, which do not shift load to capture value from time-varying rates. "Flexible devices" are able to take advantage of time-varying rates by preheating or precooling in times of low-cost electricity, in order to use less energy during high-cost times. We compare these heat pump systems to natural gas systems in all geographies. We also evaluate heating oil and propane in Rhode Island, as these fuels are still common in New England.

All scenarios assume the purchase and installation of new equipment. In electric scenarios, households are installing heat pump water heaters and air-source heat pumps for space conditioning. In fossil fuel scenarios, households are installing fossil-fuel-fired water heaters and furnaces. We analyze the cost and emissions of replacing only the fossil fuel water and space heating, as well as simultaneously replacing an air conditioning unit.

We model load and consumption for both water heating and space conditioning on 15-minute increments for a full year, using 2016 weather data.

## WATER HEATING

The load profile for water heating is the same as used in RMI's *The Economics of Demand Flexibility Report*, sourced from The Northwest Energy Efficiency Alliance's "Residential Building Stock Assessment."[56] This reflects one customer load profile; other customers (e.g., larger families with more load) would have a different load profile, or might need a water heater larger than the 45 gallons we model. We use a variable coefficient of performance (COP) curve provided by Ecotope, based on lab testing of heat pump water heaters at different water temperatures. Our preheating strategies heat water to temperatures as high as 150°F and assume these devices are equipped with thermostatic mixing valves to ensure delivery of water to the customer at safe temperatures. Heat pump water heaters have resistance heating elements, which we model as turning on only to keep the average tank temperature above a minimum threshold temperature of 113°F.

## SPACE CONDITIONING

Each scenario has a retrofit and a new construction instance, to account for increased efficiency of newly constructed homes. All scenarios assume some common elements: a 2,401-square-foot single-family home with centrally ducted heating and air conditioning. The retrofit scenarios model a poorly insulated home, while new constructed homes model a well-insulated and efficient home. Further building details are below. We use EnergyPlus to determine the heating and cooling load in 15-minute increments for each home and geography. We use performance characteristics for cold climate heat pumps from the Northeast Energy Efficiency Partnerships' cold climate air-source heat pump list.[57] To optimize for time-varying electric rates, we apply preheat and precool strategies. We assume existing air conditioners to be have a seasonal energy efficiency rating (SEER) of 14, slightly less efficient than new air conditioning systems with a SEER of 16. The heat pumps modeled have SEER 18 air conditioning performance.

| GEOGRAPHY | HOME TYPE | SEER | SEER | TONNAGE |
|---|---|---|---|---|
| CHICAGO, IL | Retrofit | Heat pump | 18 | 5 |
| | | Existing AC | 14 | N/A |
| | | New AC | 16 | 5 |
| | New construction | Heat pump | 18 | 2 |
| | | New AC | 16 | 2 |
| HOUSTON, TX | Retrofit | Heat pump | 18 | 5 |
| | | Existing AC | 14 | N/A |
| | | New AC | 16 | 5 |
| | New construction | Heat pump | 18 | 3 |
| | | New AC | 16 | 3 |
| OAKLAND, CA | Retrofit | Heat pump | 18 | 34 |
| | | Existing AC | 14 | N/A |
| | | New AC | 16 | 4 |
| | New construction | Heat pump | 18 | 2 |
| | | New AC | 16 | 2 |
| PROVIDENCE, RI | Retrofit | Heat pump | 17.8 | 5 |
| | | Existing AC | 14 | N/A |
| | | New AC | 16 | 5 |
| | New construction | Heat pump | 17.8 | 2 |
| | | New AC | 16 | 2 |

| TECHNOLOGY | WATER HEATING COP | SPACE HEATING COP |
|---|---|---|
| **Air-source heat pump** | 2.53–2.64 | Varies |
| **Natural gas** | 0.62 | 0.95 |
| **Heating oil** | 0.59 | 0.85 |
| **Propane** | 0.62 | 0.95 |

| HOME TYPE | GEOGRAPHY | WALL U | ROOF U | WINDOW U | ACH (INFILTRATION) |
|---|---|---|---|---|---|
| NEW CONSTRUCTION | **Oakland** | 0.061 | 0.543 | 0.350 | 0.224 |
| | **Chicago** | 0.061 | 0.543 | 0.320 | 0.264 |
| | **Providence** | 0.061 | 0.543 | 0.320 | 0.254 |
| | **Houston** | 0.087 | 0.543 | 0.400 | 0.309 |
| RETROFIT | **Oakland** | 0.200 | 0.543 | 0.780 | 0.736 |
| | **Chicago** | 0.087 | 0.543 | 0.511 | 0.875 |
| | **Providence** | 0.087 | 0.543 | 0.511 | 0.841 |
| | **Houston** | 0.259 | 0.543 | 0.78 | 0.613 |

## ENERGY COSTS

| CITY | ENERGY SOURCE | RATE | PRICE |
|---|---|---|---|
| OAKLAND | Electricity | PG&E E-TOU-C[58] | see next table |
| | | 3:1 TOU (representative) | see next table |
| | Gas | Baseline, $/therm | 1.2616 |
| | | Excess, $/therm | 1.7930 |
| CHICAGO | Electricity | ComEd flat bundled,[59] $/kWh | 0.1110 |
| | Gas | Customer Charge, $/month | 33.4700 |
| | | Heating customer,[60] $/therm | 0.5617 |
| PROVIDENCE | Electricity | A-16 supply + delivery,[61] $/kWh | 0.1889 |
| | Gas[62] | Customer Charge, $/month | 13.0000 |
| | | Head, $/therm | 1.2262 |
| | | Tail, $/therm | 1.0600 |
| | Propane | EIA average of 2017 price,[63] $/gallon | 3.6467 |
| | Heating Oil | EIA average of 2017 price, $/gallon | 2.8946 |
| HOUSTON | Electricity | Free Nights,[64] $/kWh 6 a.m.–9 p.m. | 0.1959 |
| | Electricity | Flat Rate,[65] $/kWh | 0.1069 |
| | Gas | Centerpoint,[66] $/therm | 0.6240 |
| | | Customer charge,[67] $/month | 15.7500 |

## CALIFORNIA TOU RATES

| | DEFAULT TOU ($/KWH) | 3:1 TOU ($/KWH) |
|---|---|---|
| **Weekday Summer Off-Peak** | 0.28037 | 0.20 |
| **Weekday Summer Peak** | 0.33456 | 0.60 |
| **Weekday Winter Off-Peak** | 0.26444 | 0.19 |
| **Weekday Winter Peak** | 0.27870 | 0.56 |
| **Weekend Summer Off-Peak** | 0.28037 | 0.20 |
| **Weekend Winter Off-Peak** | 0.26444 | 0.19 |

## DEVICE COSTS

Device costs are sourced from manufacturer input from Mistubuishi and Homewyse, the online reference for home design and construction. Installation costs are sourced from Homewyse for all retrofit scenarios. We scale installation costs for new construction homes—lower for heat pumps and higher for fossil fuel systems—based on data from BeOpt, NREL's building optimization software.

| CITY | BUILDING TYPE | SCENARIO | FIXED COSTS | |
|---|---|---|---|---|
| | | | WATER HEATER | SPACE HEATING |
| OAKLAND | Retrofit | Standard heat pump, default TOU | $2,241 | $8,641 |
| | | Flexible heat pump, 3:1 TOU | $2,416 | $8,816 |
| | | Flexible heat pump, default TOU | $2,416 | $8,816 |
| | | Natural gas, existing AC | $1,426 | $3,581 |
| | | Natural gas, new AC | $1,426 | $11,088 |
| | New Construction | Standard heat pump, default TOU | $1,828 | $4,931 |
| | | Flexible heat pump, 3:1 TOU | $2,003 | $5,106 |
| | | Flexible heat pump, default TOU | $2,003 | $5,106 |
| | | Natural gas, new AC | $1,444 | $8,017 |
| CHICAGO | Retrofit | Standard heat pump | $2,186 | $7,697 |
| | | Natural gas, existing AC | $1,365 | $3,450 |
| | | Natural gas, new AC | $1,365 | $10,140 |
| | New Construction | Standard heat pump | $1,807 | $4,840 |
| | | Natural gas, new AC | $1,382 | $7,791 |
| PROVIDENCE | Retrofit | Standard heat pump | $2,132 | $7,522 |
| | | Natural gas, existing AC | $1,306 | $3,323 |
| | | Natural gas, new AC | $1,306 | $9,853 |
| | | Heating oil, new AC | $2,175 | $9,534 |
| | | Heating oil, existing AC | $2,175 | $3,004 |
| | | Propane, new AC | $1,359 | $9,853 |
| | | Propane, existing AC | $1,359 | $3,323 |
| | New Construction | Standard heat pump | $1,786 | $4,752 |
| | | Natural gas, new AC | $1,322 | $7,573 |
| | | Heating oil, new AC | $2,190 | $6,700 |
| | | Propane, new AC | $1,375 | $7,573 |
| HOUSTON | Retrofit | Standard heat pump, flat rate | $2,062 | $8,027 |
| | | Standard heat pump, Free Nights | $2,062 | $8,054 |
| | | Flexible heat pump, Free Nights | $2,062 | $8,049 |
| | | Natural gas, existing AC | $1,228 | $3,156 |
| | | Natural gas, new AC | $1,228 | $10,114 |
| | New Construction | Standard heat pump, flat rate | $1,759 | $5,770 |
| | | Standard heat pump, Free Nights | $1,759 | $5,770 |
| | | Flexible heat pump, Free Nights | $1,934 | $5,862 |
| | | Natural gas, new AC | $1,242 | $8,345 |

| | | | WATER HEATER | | | | SPACE COOLING | | | SPACE HEATING | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CITY | BUILDING TYPE | SCENARIO | ENERGY (KWH) | ANNUAL CARBON (LB.) | ANNUAL FUEL COSTS ($) | NPC ($) | ENERGY (KWH) | ANNUAL FUEL COSTS ($) | ANNUAL CARBON (LB.) | ENERGY (KWH) | ANNUAL FUEL COSTS ($) | ANNUAL CARBON (LB.) | SPACE NPC ($) |
| OAKLAND | Retrofit | Standard heat pump, default TOU | 1,258 | 1,246 | $342 | $5,754 | 1,913 | $539 | 1,959 | 2,156 | $575 | 2,108 | $17,101 |
| | | Flexible heat pump, 3:1 TOU | 1,315 | 1,301 | $274 | $5,314 | 1,938 | $496 | 1,986 | 2,011 | $423 | 1,962 | $15,501 |
| | | Flexible heat pump, default TOU | 1,257 | 1,245 | $340 | $5,916 | 1,938 | $544 | 1,986 | 2,011 | $535 | 1,962 | $16,965 |
| | | Natural gas, existing AC | 4,706 | 1,879 | $251 | $3,710 | 2,412 | $678 | 2,467 | 8,108 | $349 | 3,238 | $12,933 |
| | | Natural gas, new AC | 4,706 | 1,879 | $251 | $3,710 | 2,219 | $624 | 2,270 | 8,108 | $349 | 3,238 | $19,947 |
| | New Construction | Standard heat pump, default TOU | 1,258 | 1,246 | $342 | $4,941 | 575 | $167 | 597 | 718 | $192 | 702 | $6,513 |
| | | Flexible heat pump, 3:1 TOU | 1,315 | 1,301 | $274 | $4,502 | 610 | $182 | 633 | 674 | $142 | 660 | $6,373 |
| | | Flexible heat pump, default TOU | 1,257 | 1,245 | $340 | $5,103 | 610 | $176 | 633 | 674 | $180 | 660 | $6,661 |
| | | Natural gas, new AC | 4,706 | 1,879 | $203 | $3,290 | 713 | $206 | 740 | 1,410 | $61 | 563 | $10,447 |
| CHICAGO | Retrofit | Standard heat pump | 1,258 | 2,727 | $140 | $3,857 | 2,477 | $275 | 4,927 | 8,850 | $982 | 19,439 | $15,489 |
| | | Natural gas, existing AC | 4,706 | 1,879 | $90 | $2,187 | 3,048 | $338 | 6,076 | 23,421 | $449 | 9,352 | $17,310 |
| | | Natural gas, new AC | 4,706 | 1,879 | $90 | $2,187 | 2,804 | $311 | 5,590 | 23,421 | $449 | 9,352 | $10,373 |
| | New Construction | Standard heat pump | 1,258 | 2,727 | $140 | $3,078 | 1,501 | $167 | 2,979 | 3,800 | $422 | 8,355 | $6,540 |
| | | Natural gas, new AC | 4,706 | 1,879 | $90 | $2,204 | 1,774 | $197 | 3,533 | 10,497 | $201 | 4,191 | $11,417 |

| | | | WATER HEATER | | | | SPACE COOLING | | | SPACE HEATING | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CITY | BUILDING TYPE | SCENARIO | ENERGY (KWH) | ANNUAL CARBON (LB.) | ANNUAL FUEL COSTS ($) | NPC ($) | ENERGY (KWH) | ANNUAL FUEL COSTS ($) | ANNUAL CARBON (LB.) | ENERGY (KWH) | ANNUAL FUEL COSTS ($) | ANNUAL CARBON (LB.) | SPACE NPC ($) |
| **PROVIDENCE** | **Retrofit** | Standard heat pump | 1,258 | 1,020 | $238 | $4,697 | 2,081 | $393 | 2,026 | 6,562 | $1,240 | 5,140 | $20,886 |
| | | Natural gas, existing AC | 4,706 | 1,879 | $188 | $3,014 | 2,577 | $487 | 2,496 | 19,844 | $782 | 7,924 | $14,883 |
| | | Natural gas, new AC | 4,706 | 1,879 | $188 | $3,014 | 2,371 | $448 | 2,296 | 19,844 | $782 | 7,924 | $21,059 |
| | | Heating oil, new AC | 4,946 | 2,723 | $353 | $5,387 | 2,371 | $448 | 2,296 | 22,179 | $1,582 | 12,206 | $28,019 |
| | | Heating oil, existing AC | 4,946 | 2,723 | $353 | $5,387 | 2,577 | $487 | 2,496 | 22,179 | $1,582 | 12,206 | $21,844 |
| | | Propane, new AC | 4,706 | 2,232 | $641 | $7,199 | 2,371 | $448 | 2,296 | 19,844 | $2,703 | 9,411 | $38,555 |
| | | Propane, existing AC | 4,706 | 2,232 | $641 | $7,199 | 2,577 | $487 | 2,496 | 19,844 | $2,703 | 9,411 | $32,380 |
| | **New Construction** | Standard heat pump | 1,258 | 1,020 | $238 | $3,950 | 1,280 | $242 | 1,249 | 2,871 | $542 | 2,246 | $10,386 |
| | | Natural gas, new AC | 4,706 | 1,879 | $197 | $3,118 | 1,524 | $288 | 1,474 | 8,572 | $359 | 3,423 | $13,467 |
| | | Heating oil, new AC | 4,946 | 2,723 | $353 | $5,402 | 1,524 | $288 | 1,474 | 9,581 | $683 | 5,273 | $15,545 |
| | | Propane, new AC | 4,706 | 2,232 | $641 | $7,214 | 1,524 | $288 | 1,474 | 8,572 | $1,168 | 4,066 | $20,832 |
| **HOUSTON** | **Retrofit** | Standard heat pump, flat rate | 1,258 | 1,590 | $134 | $3,686 | 7,337 | $784 | 8,985 | 1,957 | $209 | 2,532 | $15,350 |
| | | Standard heat pump, Free Nights | 1,258 | 1,590 | $154 | $3,860 | 7,337 | $1,326 | 8,983 | 1,957 | $139 | 2,532 | $19,678 |
| | | Flexible heat pump, Free Nights | 1,761 | 2,240 | $48 | $3,072 | 8,553 | $1,287 | 10,486 | 2,570 | $136 | 3,328 | $19,286 |
| | | Natural gas, existing AC | 4,706 | 1,879 | $100 | $2,141 | 8,918 | $953 | 10,927 | 6,087 | $130 | 2,431 | $13,016 |
| | | Natural gas, new AC | 4,706 | 1,879 | $100 | $2,141 | 8,205 | $877 | 10,053 | 6,087 | $130 | 2,431 | $19,280 |
| | **New Construction** | Standard heat pump, flat rate | 1,258 | 1,590 | $134 | $2,979 | 3,615 | $386 | 4,409 | 775 | $83 | 1,001 | $8,321 |
| | | Standard heat pump, Free Nights | 1,258 | 1,590 | $154 | $3,157 | 3,615 | $596 | 4,409 | 775 | $71 | 1,001 | $10,126 |
| | | Flexible heat pump, Free Nights | 1,761 | 2,240 | $48 | $2,369 | 4,344 | $562 | 5,314 | 756 | $68 | 975 | $11,382 |
| | | Natural gas, new AC | 4,706 | 1,879 | $100 | $2,155 | 4,213 | $450 | 5,145 | 2,343 | $50 | 935 | $12,899 |

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# ENDNOTES

# ENDNOTES

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22830 Two Rivers Road
Basalt, CO | 81621 USA
www.rmi.org