Residential Building Electrification in California

Consumer economics, greenhouse gases and grid impacts

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Energy+Environmental Economics

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Energy and Environmental Economics, Inc.
44 Montgomery Street, Suite 1500
San Francisco, CA 94104
415.391.5100
www.ethree.com

Project Team:
Amber Mahone
Charles Li
Zack Subin
Michael Sontag
Gabe Mantegna
Alexis Karolides (Point Energy Innovations)
Alea German (Frontier Energy)
Peter Morris (AECOM)

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Conventions

All costs reported in this study are reported in real 2018 dollars. All references to quantities of greenhouse gas emissions are reported using units of metric tons (or tonnes), using a carbon dioxide equivalent metric with a 100-year global warming potential.

Abstract

This study evaluates the consumer economics, greenhouse gas savings and grid impacts of electrification in residential low-rise buildings across six representative homes type in six climate zones in California. Consumer economics are evaluated in three ways, by comparing: 1) upfront installed capital costs, 2) energy bills, and 3) lifecycle savings between gas-fired and electric technologies.

Prior research has suggested that electrification of buildings is likely to be a lower-cost greenhouse gas (GHG) mitigation strategy over the long-term than a heavy reliance on renewable natural gas. This study takes a closer look at the near-term consumer economics of building electrification than prior work, considering both commonly available and best-in-class electric equipment options, as well as expected near-term increases in electric and natural gas.

We confirm that the electrification of buildings represents an important opportunity to reduce greenhouse gas emissions from buildings both in the near term and long term, and can lead to consumer capital cost savings, bills savings, and lifecycle savings in many circumstances. The most promising near-term opportunities for consumer cost savings among low-rise residential building electrification options can be found in all-electric new construction, and high efficiency air source heat pumps in homes where air conditioning can be replaced with heat pumps.

However, for electrification retrofits to succeed at scale, the market for building electrification technologies should be further developed in California. Ensuring contractors understand best-practices during scoping and installation of heat pump equipment will be critical to the long-term success of an electrification market in California. Likewise, international markets in Europe and Japan offer a wider range of high-efficiency electric technologies to choose from than are available in the United States. Finally, California should encourage the development of "retrofit ready" heat pump water heaters and HVAC systems to provide consumers with more low-cost and high efficiency electric choices.

This report is available to download at: https://www.ethree.com/wp-content/uploads/2019/04/E3_Residential_Building_Electrification_in_California_April_2019.pdf

Acronyms

AEO	Annual Energy Outlook
AFUE	Annual Fuel Utilization Efficiency
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ASHP	Air-Source Heat Pump
CAISO	California Independent System Operator
CARB	California Air Resources Board
CCA	Community Choice Aggregator
CEC	California Energy Commission
CFC	Chlorofluorocarbon
CO2	Carbon Dioxide
CO2eq	Carbon Dioxide Equivalent
COP	Coefficient of Performance
CPUC	California Public Utilities Commission
DHW	Domestic Hot Water
DOE	Department of Energy
DOF	Department of Finance
DSHP	Ducted Split Heat Pump
EE	Energy Efficiency
EER	Energy Efficiency Ratio
EF	Energy Factor
GHG	Greenhouse Gas
GRC	General Rate Case
GWh	Gigawatt-hour
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HPWH	Heat Pump Water Heater

HRMF	High-Rise Multifamily
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation, and Air Conditioning
IOU	Investor-Owned Utility
kWh	Kilowatt hour
LADWP	Los Angeles Department of Water and Power
LPG	Liquefied Petroleum Gas
LRMF	Low-Rise Multifamily
LSE	Load Serving Entity
MMBtu	Million BTU
MSHP	Mini Split Heat Pump
NGO	Non-Governmental Organization
NREL	National Renewable Energy Laboratory
PG&E	Pacific Gas and Electric
PTHP	Packaged Terminal Heat Pump
RASS	Residential Appliance Saturation Survey
RNG	Renewable Natural Gas
RPS	Renewable Portfolio Standard
SB	Senate Bill
SCE	Southern California Edison
SCG	Southern California Gas Company
SEER	Seasonal Energy Efficiency Ratio
SF	Single Family
SMUD	Sacramento Municipal Utility District
TOU	Time-Of-Use
UEF	Uniform Energy Factor
VRF	Variable Refrigerant Flow
ZEV	Zero-Emissions Vehicle

ES Executive Summary and Recommendations

Study Overview

Greenhouse gas (GHG) emissions attributable to buildings in California currently represent about a quarter (25%) of the state's total emissions.[1] In order to achieve California's climate goal of an economy-wide 40% GHG reduction by 2030, greenhouse gas emissions from buildings will need to fall by 40% or more over the next decade.[2] Furthermore, to reach California's carbon neutrality goal by 2045, high levels of building electrification are likely to be required.[3]

In 2018, E3 evaluated several long-term energy and climate scenarios for the California Energy Commission (CEC), assessing how California could achieve its 2050 climate goals. That analysis suggested that electrification of buildings is likely to be a lower-cost GHG mitigation strategy over the long-term than a heavy reliance on renewable natural gas (RNG), given current trends in the industry. The 2018 study suggested that building electrification could be a lower cost carbon mitigation option than other alternatives. However, the study did not include a detailed assessment of the customer economics of building electrification, or of the market barriers and opportunities for electrification. This study addresses these issues.

[1] E3 estimate based on data from the California Greenhouse Gas Emission Inventory and the California PATHWAYS model.
[2] See Mahone et al. (2018)
[3] The 2018 Intergovernmental Panel on Climate Change report shows a dramatic increase in the levels of building electrification between 2030 and 2050 in the scenarios that are consistent with California's carbon neutral climate goal (limiting global warming to 1.5 degrees Celsius). See Figure 2.22 in Rogelj et al. (2018)

The study was jointly funded by Southern California Edison (SCE), Sacramento Municipal Utility District (SMUD), and the Los Angeles Department of Water and Power (LADWP). Energy and Environmental Economics, Inc. (E3) is the lead author of the study and completed the economic analysis. Frontier Energy developed the electrification technology specifications and performed the building simulations of the electric- and natural gas-fueled homes. AECOM developed the installed capital cost estimates for the natural gas and electrification technologies in each home type, including the costs of building retrofits, labor and other installation costs. Point Energy Innovations served as an advisor to the study and helped evaluate the current market for electric heat pump technologies.

Methodology & Assumptions

This study evaluates the consumer costs and benefits of several types of electric air source heat pumps for space heating and cooling (HVAC), heat pump water heaters, electric and induction stoves, as well as electric and heat pump clothes dryers. Each of these electric technologies are compared individually to a natural gas alternative. In addition, all-electric new construction is evaluated relative to a mixed-fuel new construction home, as well as a "retrofit package", where the gas furnace, gas water heater and air conditioner are replaced with electric heat pump options.

The study evaluates electrification in two building types: single family homes and low-rise multifamily homes. It considers three vintages for each home type: pre-1978 vintage homes that are assumed to require electric panel upgrades, 1990s vintage homes, and new construction complying with California's 2019 Title 24 building code. New construction homes are assumed to install the same size rooftop solar panel in both the gas baseline and all-electric home, and as a result the rooftop solar has a relatively minor impact on the relative bill savings between these two options. In the retrofit homes, we sought to compare comparable levels of thermal comfort in both the gas and electric HVAC alternatives. As a result, the existing gas-fired homes evaluated in the study are assumed to either already have, or be retrofitted to include, air conditioning to provide a like-for-like comparison to the heat pumps, which also provide both heating and air conditioning.

Building simulations used NREL's BeOpt software and the DOE's EnergyPlus simulation engine. The single family and low-rise multifamily building prototypes are from the California Energy Commission's Title 24 energy code. The six building types are simulated with both a natural gas baseline and an electric option across six California climate zones. These factors combined resulted in 72 unique building simulations.

The six climate zones modeled in this study include: San Francisco (CZ3), San Jose (CZ4), Sacramento (CZ12), Coastal Los Angeles (CZ06), Downtown Los Angeles (CZ09) and Riverside (CZ10). These regions cover many of the growing population centers of the state and, combined, directly represent 51% of the state's households. Another 36% of the state's households are found in similar climate zones to those studied. The remaining 13% of the state's households are in northern, mountainous, or desert climates that are not well covered by the study area.

The installed capital costs for both gas and electric technologies were developed by an experienced building technology cost-estimator, using a combination of the cost-estimator's market experience and public sources of equipment costs. This study sought to overcome many of the shortcomings in publicly available electrification technology datasets by creating an internally consistent and detailed cost build-up, reflecting regionally-specific labor costs and contractor mark-ups, as well as the installation and permitting costs of retrofits and new construction for both gas-fired and electric end uses.

The bill savings analysis is based on a forecast of residential natural gas and electric retail rates under a "current policy" or "reference" forecast. The upfront capital cost estimates and the future bill savings are used to calculate the lifecycle savings of electric options, over the expected useful lifetime of the equipment or the building. For more details on the study methodology, see Chapter 2.

This study does not assume any incentives for gas or electric equipment, nor do we assume any market transformation of the California building electrification market. As such, this analysis represents our best guess at the "current market" conditions for low-rise residential electrification. In the future, capital costs or installation costs for equipment may change, higher efficiency equipment may become available, and both natural gas and electric rates may change dramatically from the "reference case" forecast estimated here. The California building market is changing rapidly, and future policies that are currently under development, such as the implementation of SB 1477, could have a large impact on the cost-effectiveness results shown here.

Key Findings

GREENHOUSE GAS SAVINGS

Electrification of buildings — switching from fossil fuels to electricity use for space heating, water heating, cooking, and clothes drying — represents an important strategy to reduce greenhouse gas emissions. In California, the electricity mix is already relatively clean and renewable, and by 2045, 100% of the state's retail electricity sales will be met with zero-carbon resources (per SB 100)[4]. This means that using electricity to power our homes already reduces carbon emissions relative to direct-use of natural gas, and these carbon savings will increase over time as the grid become cleaner.

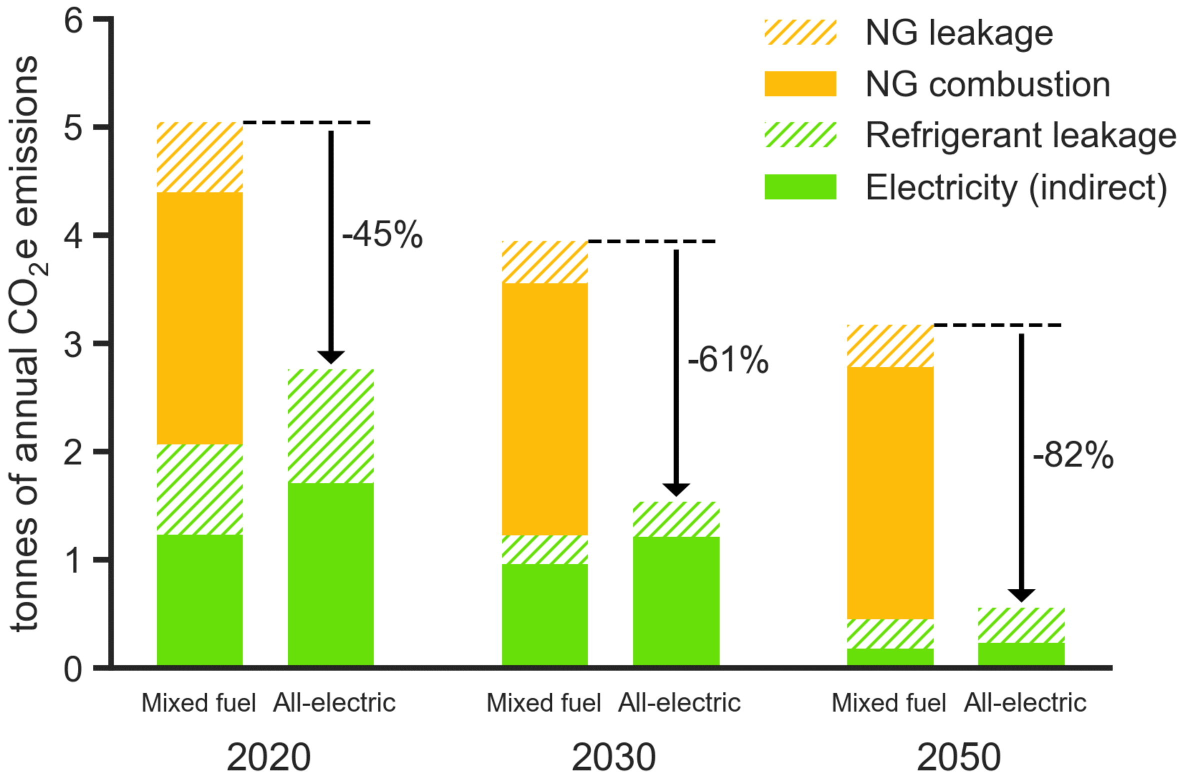
Electrification is found to reduce total greenhouse gas emissions in single family homes by ~30% – 60% in 2020, relative to a natural gas-fueled home. As the carbon intensity of the grid decreases over time, these savings are estimated to increase to ~80% – 90% by 2050, including the impacts of upstream methane leakage and refrigerant gas leakage from air conditioners and heat pumps. If the state succeeds in

[4] The details of implementing and interpreting SB 100 have not yet been clarified by the state. In this analysis, we interpret the definition of SB 100 to require about 96% zero-carbon generation by 2050, which allows over 100% of RPS-qualifying retail sales to be met with zero-carbon generation.

achieving a completely decarbonized grid by 2045, the GHG savings would be even larger in 2050. The absolute level of greenhouse gas savings in buildings depends on the size of the home, the quality of the building shell (which is generally better in newer homes), and the climate zone where the home is located.

Figure 1-1 illustrates the expected greenhouse gas emissions savings from an all-electric single family home in Sacramento in 2020, 2030 and 2050, compared to a mixed fuel home, assuming no change in the efficiency of today's commonly available electric and natural gas end uses. The largest source of greenhouse gas savings comes from eliminating on-site combustion of natural gas. Emissions from electricity decrease over time due to the state's zero-carbon generation goals. The increase in GHG emissions from refrigerant leakage associated with heat pumps in the all-electric home is relatively small, since the mixed-fuel home uses a conventional air conditioner, which also results in GHG emissions from leaked refrigerant gases. Natural gas leakage is also assumed to decrease over time as well.

Figure 1-1: Annual GHG emissions from a mixed-fuel and all-electric 1990s vintage home in Sacramento



Electricity emissions are based on the High Electrification scenario consistent with SB 100; see the greenhouse gas methodology section for more details. The 2030 and 2050 bars assume that the next generation of low-GWP refrigerants are used in all applicable heat pump systems modeled, including air conditioners, HVAC heat pumps, heat pump water heaters, and heat pump clothes dryers. We do not estimate refrigerant leakage from refrigerators and freezers, but these fugitive emissions would be the same in both electric and natural gas homes. We assume that by 2030, fugitive methane emissions are reduced by 40%, as mandated by the CARB Short-Lived Climate Pollutant Strategy and as previously set as a goal by the Obama administration. We based our calculations of fugitive refrigerant emissions on CARB data as described further in Appendix C.

Table 1-1: Greenhouse gas savings achieved across all-vintages of the all-electric homes, annual % reduction relative to the natural gas-fueled homes

	2020	2030	2050
Single family	33%-56%	52%-72%	76%-88%
Low-rise multifamily	25%-46%	49%-65%	74%-85%

Percentages show the percent reduction of GHG emissions achieved in an all-electric home relative to a natural gas-fueled home. Ranges represent the spread across climate zones and across vintages. Homes without AC in the mixed fuel case (new construction in climate zone 3) are excluded.

GRID IMPACTS

In California today, the grid is a summer peaking system, with peak electricity demand driven by residential and commercial air conditioning. This means that the summer peak load is used to plan system-wide capacity additions and investments. Residential building electrification (as well as commercial electrification, though not studied here), will lead to an increase in winter electricity demand across all climate zones. This study suggests that even in a relatively high residential building electrification future, buildings' contribution to statewide winter electricity demand is likely to remain lower than the residential summer peak demand levels, at least under typical weather year conditions.

In general, building electrification will contribute to a better utilization (higher load factor) of the bulk power grid. The regional and distribution-level grid impacts may have more localized impacts. For example, in regions without large air conditioning loads, such as San Francisco, the addition of electric heating loads could trigger a new winter-peak demand period, necessitating local distribution grid upgrades. Grid planners will need to monitor these local trends.

BUILDING ELECTRIFICATION CONSUMER COSTS AND SAVINGS

Near-term low-rise residential building electrification opportunities

All-electric new construction is one of the most promising near-term applications for building electrification efforts. All-electric new construction is expected to be lower cost than gas-fueled new construction homes in homes that have air conditioning, resulting in lifecycle savings of $130 - $540/year. These findings are based on commonly available technology, without incentives or intervening policies.

Retrofits to electric air source heat pumps for space heating and cooling represent another near-term savings opportunity in existing homes that have air conditioning. High capital costs of electric heat pump retrofits in existing homes are often perceived as a barrier to electrification, but this assumption was not borne out for homes that are otherwise already upgrading the air conditioning system. While HVAC systems are highly capital-intensive in general, in most cases we found capital cost *savings* when replacing the combination of an air conditioner and a gas furnace with a standalone heat pump HVAC unit. Further, 87% of the simulated single family retrofit homes (all of which are assumed to have air conditioning) see lifecycle savings from switching from a gas furnace and air conditioner to an electric heat pump HVAC system.

Near-term electrification barriers and market transformation needs

While electrification can be lower cost in many cases, the incremental upfront capital costs can be higher for electrification when retrofitting the HVAC system in older homes that lack air conditioning. This is because air source heat pumps provide both air conditioning and space heating; when compared to just a gas furnace the cost of the heat pump is often higher. In general, Californians could benefit from having access to a broader range of high-efficiency, lower-cost heat pump options, including those available in international markets such as Japan and Europe, but which lack a UL listing in the United States.

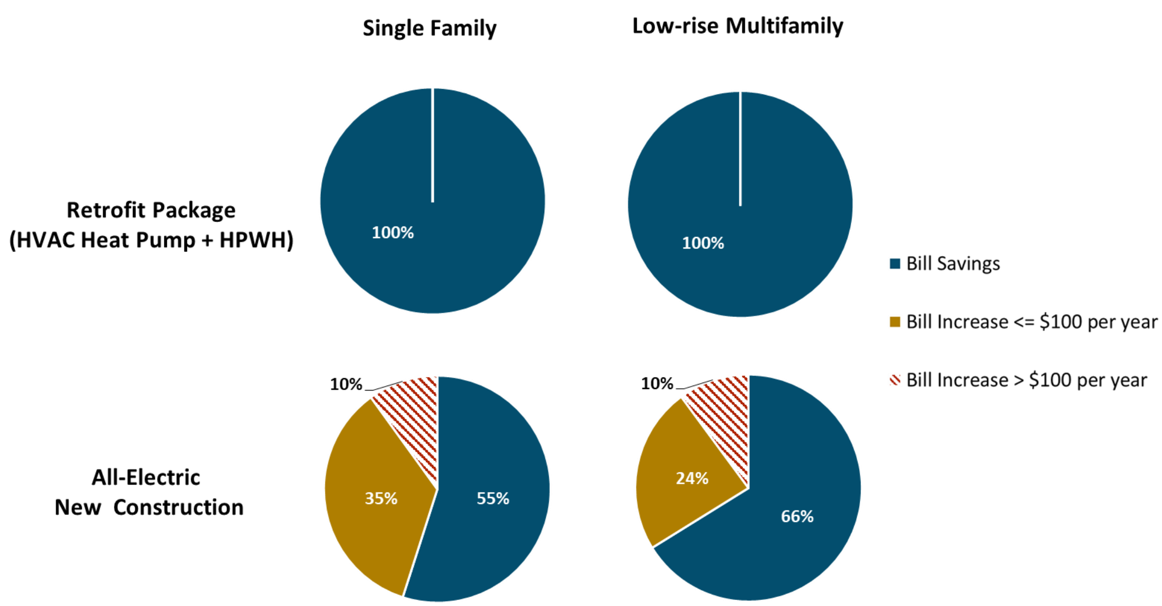
Another retrofit challenge is that older homes can require an electrical panel upgrade to support new electric loads. Electrical panel upgrades can add $2,000 - $4,000 in capital costs for some older homes that lack 200-amp electrical panels, although these are not expected to be required for the majority of existing homes. Furthermore, older homes that require electrical panel upgrades will represent a decreasing proportion of the housing stock over time as buildings are renovated or as panels are upgraded for other purposes, such as to add electric vehicle charging, rooftop solar or to add rooms or auxiliary dwelling units to an existing home. The development of low-amperage "retrofit ready" heat pump options, and lower cost solutions to the standard electrical panel upgrade package represent important areas for market transformation.

This study also evaluates the consumer economics of heat pump water heaters, electric stoves and electric clothes dryers. Heat pump water heaters are currently more expensive than conventional gas storage water heaters found in many existing homes but are comparable in cost to tankless gas water heaters which have become the norm in new construction and in home renovations. Heat pump water heaters have mixed results for lifecycle costs but can generate lifecycle savings when water heater retrofits are combined with heat pump HVAC retrofits. Electric stoves and clothes dryers are not found to generate lifecycle savings for customers under today's rates in most cases and represent end-uses that may benefit from different electric rate designs, or from a longer-term market transformation effort.

Figure 1-2 summarizes the bill savings results across all six climate zones for the simulated pre-1978 and 1990s vintage homes with the "retrofit package", replacing both the HVAC system and water heater with heat pumps, as well as the bill savings results for new construction single family and low-rise multifamily homes.

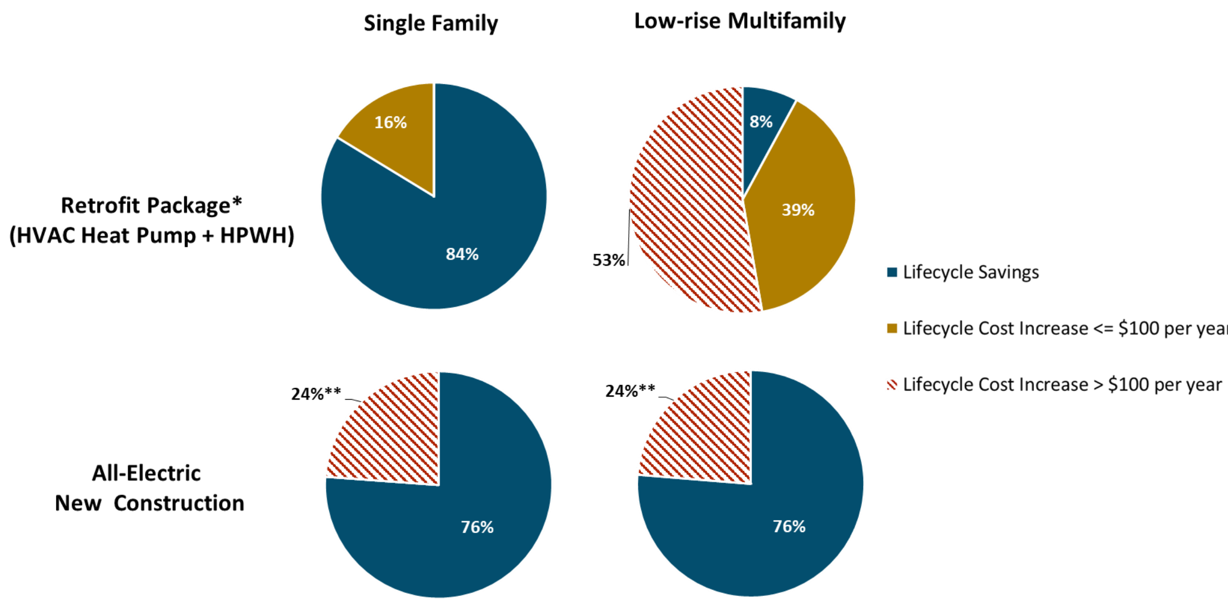
Figure 1-3 summarizes the lifecycle savings results across all six climate zones for the retrofit and new construction homes. Lifecycle savings represent the difference between the annualized capital costs and operating costs of gas equipment versus electric equipment.

Figure 1-2 Share of simulated households with bill savings from adopting electric end uses; results are weighted by the estimated share of households in each climate zone and utility service territory



The building simulation results are weighted using the share of households in each combination of climate zone and utility, as described in section 2.2.1., to create this summary figure. Average bill costs of HVAC heat pumps are compared against a combined gas furnace and air conditioner (AC) system except for a new construction home in San Francisco (Climate Zone 3) where we assume all homes do not have AC. For retrofit homes, we show the average bill impact of electrifying HVAC and water heating systems at the same time. For new construction, we look at an all-electric home with all four appliances modeled electrified.

Figure 1-3 Share of simulated households with lifecycle savings from adopting electric end uses; results are weighted by the estimated share of households in each climate zone and utility service territory



The building simulation results are weighted using the share of households in each combination of climate zone and utility, as described in section 2.2.1., to create this summary figure.
* We assume that all consumers in retrofit homes have or would install air conditioning in the mixed fuel baseline.
** This category corresponds to buildings modeled in San Francisco (Climate Zone 3) that we assumed would not install air conditioning in the gas baseline home. 100% of all-electric new construction single family and low-rise multifamily homes that include air conditioning show lifecycle savings.

Recommendations

California policymakers are already starting to evaluate policy options around building decarbonization. The Final 2018 Integrated Energy Policy Report (IEPR) Update Volume II, released by the CEC in January 2019, dedicates the first chapter of the report to building decarbonization and includes an important set of policy recommendations.[5] Likewise, the California Public Utilities Commission has recently opened a new rulemaking proceeding on Building Decarbonization. Without presupposing the outcome of these ongoing policy dialogues, we suggest a few broad policies to encourage higher levels of building electrification in California.

Overall, building electrification represents an important strategy for reducing greenhouse gas emissions in California. Additional strategies will need to be pursued in parallel if California is to meet its climate goals, including continued improvements in electric and natural gas energy efficiency in buildings, the development of sustainable renewable natural gas for remaining natural gas consumption in non-converted buildings and in industry, and mitigation of methane leaks and high global warming potential gases. However, given the long lifetimes of buildings and building equipment, California cannot afford to miss windows of opportunity to electrify building end uses where possible. Near-term policies are needed to encourage higher rates of building electrification, when benefits can be created for customers and for society.

Electrification can support sustainability and equity policy goals. For example, heat pump HVAC systems provide a climate *adaptation* advantage, because they provide both air conditioning and heating. Air conditioning, along with better building design and more resilient communities, can help protect public health in low-income and vulnerable communities as heat waves become more severe under climate change. Likewise, California is currently facing a historic housing affordability crisis driven largely by a housing supply shortage. In this study we found that all-electric new homes can reduce building costs. By prioritizing the construction of new and affordable housing, and ensuring that these homes are designed to be highly efficient, California has a greater chance of meeting its climate policy goals while protecting its most vulnerable residents.

[5] See Bailey et al. (2019).

Despite the positive economic results for many homes, current heat pump market penetrations are much lower than the economic potential. The following recommendations suggest ways to address the market barriers to heat pumps, accelerating adoption so that building electrification may occur quickly enough to play a role in meeting the state's climate goals.

Our recommendations can be summarized into the following five points, which are elaborated on below:

1. Incentivize all-electric new construction and update the building code
2. Incentivize high-efficiency heat pump HVAC, particularly in areas with high air conditioning loads
3. Ensure efficient price signals are conveyed in electric and natural gas rates
4. Develop a building electrification market transformation initiative
5. Align energy efficiency goals and savings with GHG savings opportunities

1. INCENTIVIZE ALL-ELECTRIC NEW CONSTRUCTION AND UPDATE THE BUILDING CODE

+ **All-electric new construction in residential low-rise homes appears to be among the most promising near-term ways to save consumers money and reduce GHG emissions and could be incentivized in the near term to help transform the market.** It avoids the costs and hassle associated with retrofits, and in most cases, we found that all-electric new construction offered lifecycle cost savings for residents. Savings could be larger if capital costs were reduced, if higher efficiency electric technologies were available, or if the costs of gas distribution interconnection were more directly reflected in the cost of new construction.
+ **Align building standards with GHG savings opportunities.** In California's building code, the current approach to assessing cost effectiveness (Time Dependent Valuation [TDV]) does not fully measure or fully value GHG emissions savings. The CEC is working to update the TDV metric in the next code cycle to allow the emissions benefits of building electrification to be appropriately valued and considered in new construction design decisions. In addition, the building code could include a GHG emissions performance standard for new buildings. The estimated GHG emissions

from a building would be calculated based on the efficiency and simulated performance of the building, combined with a long-term forecast of emissions from electricity and pipeline gas, using policy goals or verifiable commitments from utilities. The GHG performance standard could become stricter in each code cycle, as the state's climate goals become more stringent. A GHG emissions performance standard is a technology-neutral way to encourage the decarbonization of buildings.

+ **New construction homes should be designed to be "electrification-ready",** with sufficient electrical amperage and circuitry in the right places for future electric HVAC, water heating, cooking, and clothes drying equipment, as well as for electric vehicles (EVs) where possible. Given the long lifetime of buildings and heating equipment and the cost of upgrading electrical infrastructure in existing buildings, new construction is the ideal time to design buildings to be prepared for an all-electric future. In retrofit homes, electrical panel upgrades to accommodate room additions, electric vehicles, and rooftop solar panels can be specified to ensure that there is sufficient electric panel capacity for electric HVAC, water heating, cooking and clothes drying.
+ **Factor fugitive emissions from high-GWP refrigerants and natural gas leakage into GHG metrics.** Future building standards metrics should incorporate the emissions from high-GWP refrigerant leakage as well as methane leakage in the gas distribution system and within houses. This will yield a balanced and comprehensive perspective on emissions from gas and electric technologies and encourage best practices for using lower-GWP refrigerants and reducing methane leakage.

2. INCENTIVIZE HIGH-EFFICIENCY HEAT PUMP HVAC, PARTICULARLY IN AREAS WITH HIGH AIR CONDITIONING LOADS

California should consider developing programs to incentivize:

+ **Heat pump HVAC systems in residential low-rise retrofit homes, where central air conditioning is needed/wanted. Higher efficiency heat pumps should be encouraged above existing code minimums.** Heat pumps provide both space heating and space cooling and are found to be cost-effective in homes where they can serve both these purposes. While the 2015 federal code minimum for heat pump HVAC systems encourages high efficiency heat pump installations, higher efficiency heat pump HVAC products are readily available in the market and provide customer benefits. Heat pump HVAC systems with higher efficiencies (Heating Seasonal Performance Factor [HSPF] of 10 or higher) create lifecycle savings for residential customers in homes that require air conditioning.

+ **HVAC heat pumps to replace space heating currently provided by propane, distillate, or electric resistance heat.** The economic benefits of replacing high cost fuels with electric HVAC heat pumps have been demonstrated in other studies. Replacing high cost heating fuels, including propane, distillate, and electric resistance heat with high efficiency HVAC heat pumps represents "low-hanging fruit" when it comes to savings customers money and reducing GHG emissions.

+ **Encourage the installation of high efficiency HVAC heat pumps rather than standalone central AC units whenever possible**. The capital cost analysis found that HVAC heat pumps are generally cheaper than the combined cost of a new gas furnace and standalone central air conditioner, and bill savings are seen in most home types as well. Incentives could take advantage of these cost savings to encourage consumers to install an HVAC heat pump when replacing an air conditioner whenever it makes sense for that building. This will give the home the option to use gas heating or electric heating (with the option to not replace the gas furnace upon failure), while providing high efficiency air conditioning during the summer.

+ **Consider early replacement programs for older gas furnaces and gas water heaters.** These programs would be designed to avoid the practical challenges around "emergency" replacement of equipment upon failure, when there is less time to retrofit a home to electric technologies. Early replacement programs could also target the oldest, least efficient equipment, thereby maximizing bill savings and GHG savings.

+ **Target incentives and low-cost financing to landlords and low-income consumers to overcome capital cost barriers and ensure that clean energy benefits are enjoyed by all communities**. Upfront capital cost barriers will prevent many consumers from investing in new equipment unless they absolutely have to when their existing equipment fails. This is particularly true for low-income customers. The CPUC could call for proposals or pilots for innovative business models, such as ConEdison's proposal for financing small to medium commercial HVAC heat pumps and developing a utility-owned ground-source heat pump program[6]. Other financing options to explore include on-bill financing programs like the "Pay As You Save (PAYS®)" programs. Furthermore, incentives targeting landlords would allow renters to take advantage of bill savings from efficient heat pumps.

3. ENSURE EFFICIENT PRICE SIGNALS ARE CONVEYED IN ELECTRIC AND NATURAL GAS RATES

+ **Design more efficient electricity rates.** Today's electricity rates are largely designed based on volumetric charges (i.e. $/kWh of use). However, many costs on the electric grid do not vary with the quantity of electricity used, but are rather based on system-wide, and distribution level costs. More efficient, cost-based electric rates would remove disincentives for electrification and could better align customer choices with socially beneficial outcomes. While electric rates do not need to be designed to preferentially encourage building electrification, they should at least be evaluated to ensure that they do not discourage electrification. For example, electric rates could collect more of the "fixed costs" via fixed charges rather than volumetric rates, which tend to penalize electrification. In addition, in regions with time-of-use (TOU) rates, the TOU periods should be aligned with system costs as well as GHG emissions on the grid.
+ **Higher carbon prices, or complementary policies aimed at reducing the GHG emissions from natural gas, would better align customer's economic incentives with the state's climate goals**. This study finds that electrification of water heating and HVAC results in substantial GHG savings in all cases at today's emission rates. Moreover, the electricity system is required by SB 100 to reduce emissions to near zero by 2045. No comparable policy exists for the natural gas system to reduce GHG emissions. Yet, carbon prices in California, ranging between $12 and $22/tonne as of early 2019, have been too small to effectively signal to customers the GHG benefits associated with fuel-switching to electricity. In 2016 the US Environmental Protection Agency (EPA) calculated a mid-range "social cost of carbon" representing the global harms of incremental CO_2

[6] Petition of Consolidated Edison Company of New York Inc. for Approval of the Smart Solutions for Natural Gas Customers Program, Case 17-G-0606, December 20th, 2018.

emissions of $42/tonne for emissions occurring in 2020, with a more recent study estimating an *order of magnitude* larger value represented a mid-range estimate (Ricke et al. 2018).

+ **Consider requiring builders, rather than ratepayers, to pay for the full cost of new gas distribution hookups.** Currently, utilities cover a portion of the cost of new gas hookups to buildings, anticipating that these costs will be recovered from ratepayers through future revenues. These discounts can be up to 50% of the total estimated installed costs to complete a distribution main extension.[7] However, continued natural gas distribution revenue growth is not guaranteed in a carbon-constrained future, and these gas distribution fixed costs may become shared among a shrinking base of natural gas customers. Ensuring that new gas hook-ups are paid for by the builder at the point of construction could mitigate future cost increases for existing gas customers.

4. DEVELOP A RESIDENTIAL BUILDING ELECTRIFICATION MARKET TRANSFORMATION INITIATIVE

Market transformation can mean many things to many people. In this context, we mean that the residential building electrification market would benefit from having access to a wider range of high efficiency and "retrofit" ready products, including some that are already available in international markets, as well as a better trained workforce to ensure experienced installers and service providers are readily available and operating competitively across the state, and more information available to consumers about electrification options, costs and benefits. A few recommendations describing what such a market transformation initiative could include are described below:

+ **Encourage the development of retrofit-ready electrification technology options for older homes.** In general, 200-amp electrical service is needed to serve a home with both a heat pump HVAC system and heat pump water heater. While most newer homes have 200-amp service, many

[7] See for example PG&E's Gas Rule No. 15 for gas main extensions: https://www.pge.com/tariffs/assets/pdf/tariffbook/GAS_RULES_15.pdf

older homes in California do not (data is not readily available on the share of homes in each category). In this study, the electrical panel upgrade costs triggered by the adoption of heat pump HVAC and heat pump water heating units together were large enough to create net costs instead of net savings for some of the low-rise multifamily homes that were modeled (the panel upgrade costs were applied to pre-1978 vintage single family homes in this situation). An area for on-going market transformation is in developing more “retrofit-ready” heat pump options, that are small enough to fit in existing spaces and require lower current, to avoid the need for an electrical panel upgrade in these older, retrofit homes.

+ **Educate consumers about building electrification options**. Consumers may have preconceptions about electric technologies, based on earlier generations of electric heat pumps and electric resistance stoves. Some consumers are entirely unfamiliar with heat pump technologies; others are unaware of newer options like ductless heat pumps and induction stoves. Many consumers are not aware of the non-economic advantages of new electric technologies, such as the option for multi-zone temperature control with ductless heat pumps, or the health, safety and performance advantages of induction stoves over conventional gas stove. Customers should also be aware of other differences between electric and gas options, such as the potential for noise or vibrations from an electric heat pump condenser/compressor. Consumers generally want to know about real-world experiences from a trusted source before they make important decisions a new electric technology in their home. Ideally, they should have this information before their existing equipment fails.

+ **Workforce training and certification for electrification in buildings**. Currently, few building contractors and HVAC professionals are well-versed in building electrification technologies. Poorly installed heat pumps could create a customer backlash against the technology. Workforce training, combined with a voluntary certification program for building electrification, could provide quality assurance to customers interested in making the switch to electric HVAC or water heating. Similarly, with CPUC guidance, utilities could consider direct utility install programs to ensure electrification technologies are readily available on the truck, and that high-quality installations can be ensured. Quality control is needed for proper sizing and installation of the right heat pump equipment for each customer’s needs.

- **Coordinate with manufacturers to bring emerging technologies to the US market, including very efficient heat pumps, ultra-low global warming potential refrigerants, and retrofit-ready or low-voltage options.** Many high efficiency heat pump products available in other countries are not available in the U.S., and manufacturers may be reluctant to invest in market expansion on their own given the relatively small size of the U.S market today. State and local governments and utilities could commit to purchasing initial tranches of equipment for use in buildings they own and operate to help bring new heat pump technologies to the U.S. market.
- **Encourage lower global warming potential gases to be used in heat pumps and encourage heat pump innovation over time**. Higher incentives could be made available for appliances featuring low-Global Warming Potential (GWP) refrigerants.

5. ALIGN ENERGY EFFICIENCY GOALS AND PROGRAMS WITH GHG SAVINGS OPPORTUNITIES

- **Energy efficiency incentives should be aligned with GHG savings opportunities.** Historically, energy efficiency programs have been designed with separate goals for reducing natural gas and electricity consumption. These programs focus on cost-effective kWh and therm energy savings rather than cost-effective carbon savings. Energy efficiency programs for fuel substitution, (e.g. switching from natural gas to electric end uses), have been effectively prohibited by the current interpretation of the CPUC's "three-prong test".[8] The CPUC should update the three-prong test to directly consider carbon savings and allow incentive programs for electrification where cost-effective energy and carbon savings can be achieved. Furthermore, California should pursue a combined, all-fuels approach to cost-effectively reduce carbon emissions from buildings, reducing silos between natural gas and electrical efficiency programs.

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[8] The CPUC developed a standard to known as the "three-prong test" in the 1990s to determine whether energy efficiency program funding could be used for projects involving fuel switching. The broad objectives of the three-prong test, which are to ensure that energy efficiency programs: 1) save energy, 2) are cost-effective, and 3) not harm the environment, are valid. However, the definitions and application of the test have become outdated, and so in practice, the three-prong test has become a hurdle, preventing utilities from using energy efficiency funds to incentivize electric end uses over the direct use of natural gas. The CPUC has issued a ruling (R-13-11-005) seeking comments on possible revisions to the definition and implementation of the three-prong test, but no decision has been reached. For more information on the three-prong test, see the California Public Utilities Commission, 2013 Energy Efficiency Policy Manual, R.09-11-014, Version 5, July 5, 2013, pages 24-25: http://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/Utilities_and_Indus tries/Energy_-_Electricity_and_Natural_Gas/EEPolicyManualV5PDF.pdf.

In summary, many low-rise residential building owners and residents could already see cost and GHG savings from electrifying space heating and water heating, even in the absence of incentives or programs. However, in order to increase adoption rates of low-rise residential building electrification options in California, the state will need to develop new policies and programs such as those described above, educate and train both contractors and consumers about building electrification technologies, and encourage market transformation for building electrification technologies.

1 Introduction

1.1 Study motivation

1.1.1 CALIFORNIA'S CLIMATE GOALS

California has established itself as a global leader in reducing greenhouse gas emissions (GHGs). The state has set ambitious targets to reduce emissions 40% below 1990 levels by 2030 (40x30; Senate Bill 32 of 2016) and to achieve carbon neutrality by 2045 (Executive Order B-55-18 of 2018). Recent analysis has indicated that to meet these goals, California will need to significantly reduce emissions from direct fossil fuel combustion in buildings, which currently represent ~10% of total statewide GHG emissions[9].

Greenhouse gas emissions from electricity use in buildings are already on the decline, thanks to the state's renewable portfolio standard and energy efficiency efforts. However, GHG emissions from natural gas use in buildings has remained flat in recent decades. California Assembly Bill 3232 (2018) calls for the California Energy Commission to assess how to achieve a 40% reduction in GHG emissions by 2030 within the state's residential and commercial buildings. Achieving this goal in buildings in 2030, while remaining on the path to carbon neutrality by 2045, will require a major transformation of the existing building stock, and new construction, in California.

[9] See Mahone et al. (2018).

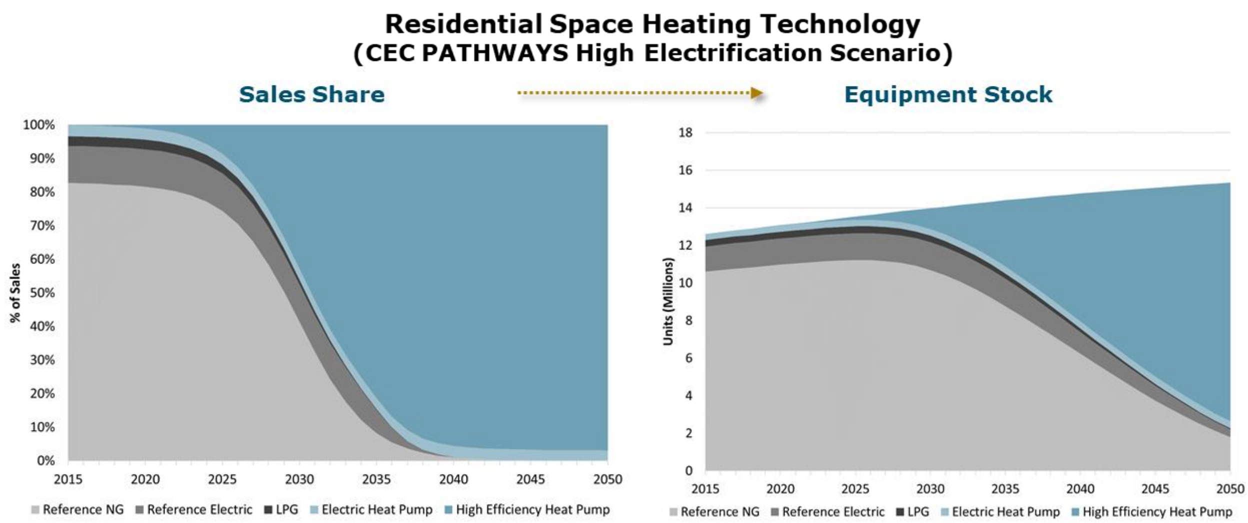
1.1.2 BUILDING ELECTRIFICATION IN THE CONTEXT OF CALIFORNIA'S GREENHOUSE GAS REDUCTION GOALS

There are two primary strategies to mitigate direct GHG emissions from buildings: 1) natural gas energy efficiency combined with extensive use of renewable natural gas (RNG), and 2) electrification of fossil fuel end uses in buildings. Neither one of these strategies have seen wide adoption to date, and both face implementation challenges.

In the near-term, progress is needed on both fronts. In the long-run, electrification in buildings appears to be a lower-cost GHG mitigation strategy from a societal perspective, particularly if the supply of renewable natural gas is limited, and limited progress is made on the commercialization of carbon neutral synthetic fuels and power-to-gas technologies. That was a key conclusion from E3's 2018 evaluation of several long-term energy and climate scenarios for the California Energy Commission (CEC), assessing how California could achieve its 2050 climate goals. The High Electrification scenario was one of those scenarios, and was among the lower cost, and lower risk scenarios evaluated.

In the High Electrification scenario, the sales share of electric heat pumps for residential space heating and water heating ramps up quickly, from less than 10% at present, to about 50% in 2030, and to 100% of all new sales in 2040 (Figure 1-1.). In this scenario, heat pumps for space heating and water heating saved 27 MMT CO_2e in 2050, relative to a 2050 economy-wide emissions target of 86 MMT statewide. While this scenario assumed that equipment is only replaced at the end of its useful lifetime, achieving this level of adoption of building electrification by 2050 would still require retrofitting at least half the existing residential building stock, more than 7 million homes, with electric heat pump space heating. Buildings, and the space heating and water heating equipment used in buildings, are long-lived and slow to change – which is why any effort to electrify buildings would need to begin in the early 2020s, in order to assure a reasonable pace of transitioning the state's building stock without causing disruption in people's homes.

Figure 1-1. Residential Space Heating Technology Sales Share and Equipment Stock in the High Electrification Scenario



Source: Mahone, 2018.

The market share trajectory shown in the figure above is based on what might be required to meet the state's climate goals, rather than a detailed assessment of consumer economics and existing market barriers.

1.1.3 PREVIOUS STUDIES OF BUILDING ELECTRIFICATION

Other regions, including the U.S. Northeast and Northwest, have begun to explore the economic and practical implementation issues around "beneficial electrification" as a greenhouse gas reduction measure (Regulatory Assistance Project, NYSERDA, Northeast Energy Efficiency Partnership). The National Renewable Energy Laboratory assessed the potential for electrification in buildings, transportation, and industry throughout the US, including reviewing the likelihood for future heat pump innovation.[10]

[10] See Mai et al. (2018).

However, California has unique climate, building stock, and energy prices compared with the rest of the US. Several recent studies have focused on the economics of electrification in California. The Rocky Mountain Institute analyzed case studies for four national locations, including Oakland, and highlighted three situations when building electrification is generally expected to be cost-effective: 1) when replacing oil or propane, 2) in new construction, and 3) when replacing both an air conditioner and a furnace.[11] A recent study from the Natural Resources Defense Council, performed by Synapse Energy Economics, also found the potential for both capital cost savings and bill savings from electrification in California, and identified a set of next steps to encourage building electrification in the state.[12] This study confirms many of the high-level findings of these previous studies, while taking a more detailed look at the consumer economics of residential electrification across more heat pump technologies, climate zones, and building types within California (Section 1.1.5).

1.1.4 HISTORICAL POLICY BARRIERS TO BUILDING ELECTRIFICATION & WHAT'S CHANGED

Historically, the California Public Utilities Commission (CPUC) and CEC enacted energy efficiency policies to reduce electricity consumption and encourage on-site use of natural gas over electric heating. This made sense, because electricity was largely generated from fossil fuels, in relatively inefficient powerplants, separated from the customer by transmission and distribution losses which further wasted energy. Meanwhile, on-site combustion of natural gas for heating was encouraged because it was more efficient than conventional electric resistance heating fueled by a fossil power plant.

It was in this context that the CPUC developed a standard known as the "three-prong test" in the 1990s to determine whether energy efficiency program funding could be used for projects involving fuel

[11] See Billimoria et al. (2018).

[12] Hopkins, Asa, K. Takahashi, D. Glick, M. Whited, "Decarbonization of Heating Energy Use in California Buildings," Synapse Energy Economics, October 2018.

switching.[13] The broad objectives of the three-prong test, which are to ensure that energy efficiency programs: 1) save energy, 2) are cost-effective, and 3) not harm the environment, are valid. However, the definitions and application of the test have become outdated, and so in practice, the three-prong test has become a hurdle, preventing utilities from using energy efficiency funds to incentivize electric end uses over the direct use of natural gas. The CPUC has issued a ruling (R-13-11-005) seeking comments on possible revisions to the definition and implementation of the three-prong test, but no decision has been reached.

California's energy efficiency programs, including the standards in the three-prong test, must be updated to reflect current requirements for low-carbon electricity on the grid, and to reflect the state's long-term climate goals. Today, California's electricity grid is relatively clean, with about 50% from renewable or zero carbon generation, and almost no coal generation. The grid will only get cleaner as load-serving entities comply with Senate Bill (SB) 100, which requires a 60% renewable portfolio standard (RPS) by 2030 and 100% of retail sales to be served by zero carbon electricity by 2045.

Meanwhile, increasingly efficient electric heat pumps are available in the market. Modern air-source electric heat pumps are 3 to 4 times more efficient than electric resistance or gas heaters, especially in California's mild climate. This means that a high-efficiency electric heat pump, powered by electricity from a natural gas combined cycle power plant, will generally consume less natural gas in total than the on-site combustion of natural gas in a conventional furnace.

Energy efficiency is one key component or "pillar" of deep decarbonization, along with electrification and the use of low carbon fuels (Mahone, 2018). The challenge at hand for regulators and policymakers today is to ensure that the definitions and policies around energy efficiency in buildings and appliance standards

[13] California Public Utilities Commission. 2013. Energy Efficiency Policy Manual, R.09-11-014, Version 5, July 5, 2013, pages 24-25: http://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/Utilities_and_Indus tries/Energy_-_Electricity_and_Natural_Gas/EEPolicyManualV5PDF.pdf.

are updated to reflect the state's climate goals, including by enabling and encouraging electrification and the use of low-carbon fuels in buildings.

1.1.5 GOALS OF THIS STUDY

This report evaluates the factors affecting market adoption of electric end uses in residential buildings in California, including retrofits of existing mixed-fuel buildings, as well as new all-electric construction. The key goal of this study is to provide a more detailed set of customer-focused analyses of building electrification options than have been previously undertaken in California. Elements of this study include:

+ An assessment of impacts of building electrification using detailed electric and natural gas rate structures compared to hourly electricity demands;
+ A detailed breakdown of electrification and natural gas equipment capital costs, labor costs, and installation costs across different regions of California;
+ Scenarios to assess the changing dynamics in customer costs over time, with two scenarios of how electric and natural gas rates may change over time, as well as sensitivities with improved heat pump performance and lower capital costs over time;
+ A disaggregation of the impacts of building electrification by end-use, focusing on HVAC, water heating, cooking and clothes drying in different building types and climate zones across the state;
+ An identification of priority actions and market segments for future utility or state programs to encourage building electrification.

This study focuses on the economics of electrification with current market and policy conditions and is not intended as a detailed program design assessment for building decarbonization. Likewise, previous work[14] has highlighted the need for a more detailed assessment of the role of the natural gas system in the context of California's climate goals. California will need to develop a natural gas transition strategy if building electrification proves to be a successful decarbonization strategy, particularly for natural gas

[14] See Mahone et al. (2018).

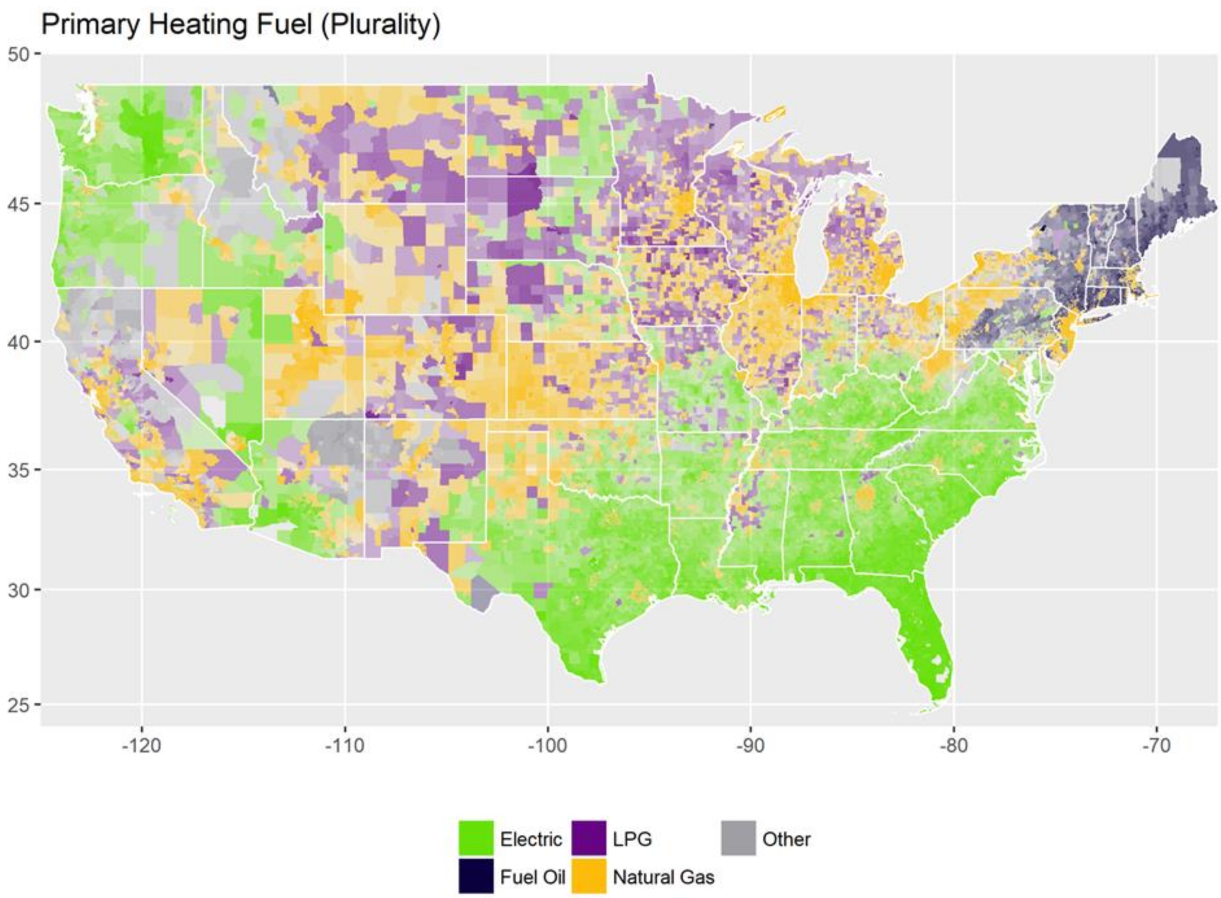
customers and distribution utilities. The potential implications of this gas transition strategy are outside the scope of this study.

1.2 Building electrification market overview

In the United States, the use of electric space heating is highest in the South and Pacific Northwest. These regions are characterized by mild winters and historically, cheap electricity and limited natural gas distribution (Figure 1-2.). Historically, these regions have relied on lower efficiency electric resistance heat and older technology heat pumps. However, as heat pump technology has improved, electric heat pumps are becoming an increasingly attractive option even in very cold climates. Electric heat pump adoption has grown in the Northern US, particularly in states like Maine and Vermont, largely displacing higher cost heating fuels like fuel oil, wood, coal, and propane[15].

[15] See Lapsa et al. (2017)

Figure 1-2. Residential Electric Space Heat Market Share in the United States



Data from the American Community Survey (2016).

While modern, higher efficiency heat pumps still represent a relatively small share of most segments of the US heating market, they represent a growing share of HVAC deployments in new homes, particularly in the Southern US. The Energy Information Administration's latest Residential Energy Consumption Survey (RECS) estimates 12 million American households (10% of total households) currently use electric heat pumps as their primary space heating equipment, with 40 million households using electricity as their primary heat source. Over 70% of households relying primarily on heat pumps are in the South[16].

In the US Northeast and Northwest, policymakers and utilities have begun to develop rebates and incentives for electric heat pump adoption, including in New York, Washington, and Vermont. These policies are generally viewed in the context of energy efficiency, with the added benefit of displacing fuel oil or other expensive fuels; however, using electric heat pumps to reduce greenhouse gas emissions from fossil fuels is increasingly part of the policy conversation in these regions. Further, policymakers are increasingly interested in electric heating as a method for renewables integration and electric system management[17].

In California, despite its moderate climate, the use of electric heat remains limited, outside of rural areas that lack natural gas. Electric heat pump adoption in California remains limited largely due to the relatively low cost of natural gas and widespread natural gas distribution system in urban areas. The California Energy Commission's 2009 Residential Appliance Saturation Survey (RASS) estimates heat pump space heating accounted for only one percent of California households.

Many municipal utilities and Community Choice Aggregators (CCAs) in California, including the Sacramento Municipal Utility District (SMUD), Los Angeles Department of Water and Power (LADWP), Marin Clean Energy, and Sonoma Clean Power have begun to offer incentives and programs for electric heat pumps as a cost-saving and greenhouse-gas saving measure. Some of these programs focus on incentivizing electrification in new homes.[18]

[16] From the EIA Residential Energy Consumption Survey: **https://www.eia.gov/consumption/residential/data/2015/hc/php/hc6.8.php**
[17] See Billimoria et al. (2018).
[18] For a recent summary of policies and programs for building electrification, see, "Meja Cunningham, A. Ralston, M. and Wu, K., "Strategies and Approaches for Building Decarbonization," Transcendent Energy for the Building Decarbonization Coalition, 2018.

1.3 Report contents

The remainder of this report is organized as follows:

- **Section 2** describes the modeling approach applied in this analysis, including assumptions about the California housing stock and heating fuel mix, building energy simulations, customer economics, greenhouse gas impacts, and grid impacts.
- **Section 3** presents the results of the analysis.
- **Section 4** identifies barriers to electrification and potential solutions.
- **Section 5** concludes with recommendations and additional research needs.

Additionally, several appendices with additional technical details are included:

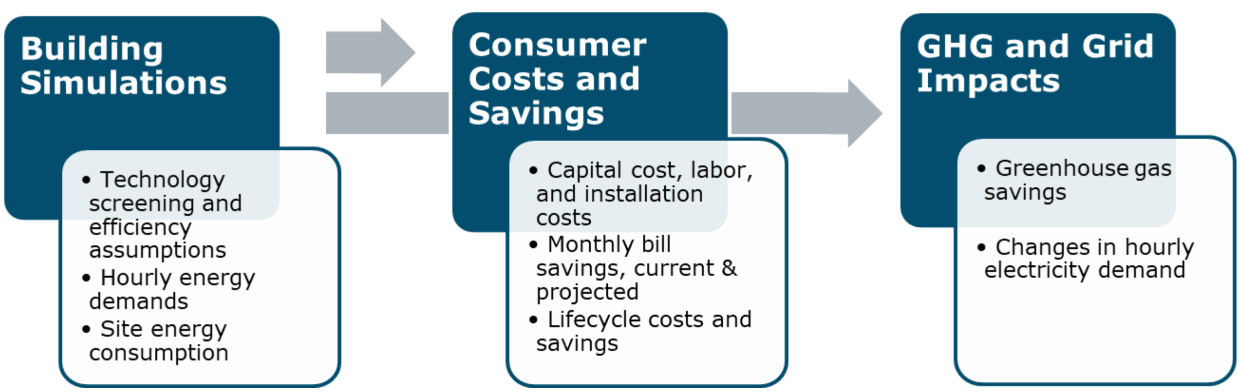
- **Appendix A: Technology Characterization and Screening** describes the criteria for selecting the appliances modeled.
- **Appendix B: Building Simulation Descriptions** describes the modeling of building energy demands.
- **Appendix C: Additional Methods Detail** for greenhouse gas calculations
- **Appendix D: Market Adoption Barriers and Potential Solutions** provides a more complete list of market barriers and solutions than the key examples discussed in Section 5.
- **Appendix E: Additional Results** provides additional charts and tables of results, including site energy savings results.

2 Modeling Approach

2.1 Methods Overview

This section describes the methods and modeling approach used in this study. At a high level, we started with data on the existing housing and appliance stock. Building simulations were used to develop estimates of hourly energy demands. This information was used to estimate the bill impacts of building electrification, which combined with estimates of the capital costs of building electrification, allowed us to calculate lifecycle costs and savings. The building simulation data was also used to evaluate the greenhouse gas savings of building electrification and changes in hourly electricity demand that could be associated with high levels of building electrification in California. Each of these steps are described in more detail below.

Figure 2-1. Analysis steps schematic

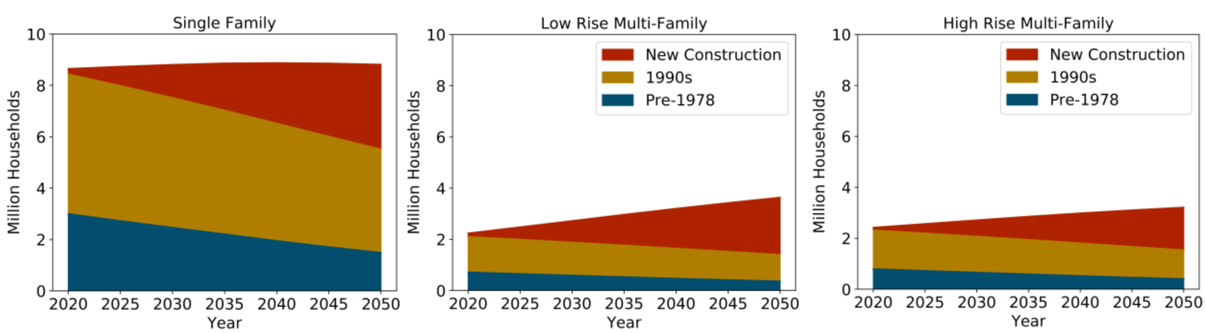


2.2 California Housing Stock and Market Potential

2.2.1 HOUSING STOCK

In 2014, California's population of 39 million resided in 13 million households, which the California Department of Finance (DOF) forecasts will grow to 50 million people by 2050, in approximately 16 million households.[19] The majority of households live in single family dwellings, although multifamily housing comprises the majority of new construction.[20] California also includes about 0.6 million mobile homes, which are not pictured, and are not studied here, but which are included in the California PATHWAYS model. The characteristics of the building stock over time determine the characteristics of the market for new appliances and the potential for electrification.

Figure 2-2: Projected residential housing stock for single family, low-rise multifamily and high-rise multifamily



Source: Based on 2019 data from the E3 California PATHWAYS model, residential building stock-rollover assuming a 75-yr mean life and that new housing keeps up with population growth

The California PATHWAYS model (Mahone et al. 2018) simulates the state building stock using historical and projected county-level population based on the DOF forecast. It assumes a stock-rollover of housing units, treating substantial building shell upgrades and retrofits as new buildings for the purposes of

[19] See http://www.dof.ca.gov/Forecasting/Demographics/projections/ (version available in 2016 was used; more recent data is now available)
[20] See http://www.dof.ca.gov/Forecasting/Economics/Indicators/Construction_Permits/

modeling building energy demands (Figure 2-2). A 75-yr mean lifetime is assumed for turnover and shell upgrades. The proportion of existing appliances is determined from the Residential Appliance Saturation Survey (RASS)[21].

The rate of new construction relative to existing homes is a key metric for assessing the potential for electrification, as logistical barriers to electrification are generally much lower for new construction than for retrofitting existing housing. New buildings naturally provide a decision point for installing an efficient technology, whereas retrofits may require cumbersome or costly adjustments to features such as ducts, electrical wiring, and appliance placement. All-electric new buildings can avoid the costs inherent in supporting dual fuel capability. Previous studies have identified new buildings as a priority for building electrification.[22] Following the assumptions in PATHWAYS, new construction is expected to represent about one half of the building stock by 2050; this means that meeting the adoption rates in the High Electrification Scenario (Section 1.1.2) will require retrofitting at least half the existing residential building stock, more than 7 million homes.

California housing construction has not kept up with population growth, with a current shortfall estimated at more than 3 million homes.[23] This is reflected in building permit data, with the 117,000 building permits issued in 2017 for new construction or substantial modifications exceeding that of any year in the last decade, which averaged 74,000. This number is short of the approximately 100,000 annual new homes required to keep up with population growth at constant household size, with no allowance for turnover of the existing housing stock. In this study, we assume that building turnover and new construction will eventually rise commensurate with a 75-year turnover of the existing building stock and population growth. We note that if this does not occur, even more retrofits may be needed than we estimate here to reach the state's climate goals. Conversely, housing policy reforms that facilitate new construction and

[21] 2003 California Residential Appliance Saturation Study (KEMA-XENERGY, Itron, and RoperASW 2004).
[22] See Billimoria et al. (2018) and Hopkins et al. (2018).
[23] See Woetzel et al. (2016).

faster turnover of existing buildings – many of which are currently overdue for upgrades – could potentially accelerate a transition to building electrification.

The two tables below show the share of the residential existing housing and new construction housing stock for single family detached and low-rise multifamily that are assumed to be located in each combination of climate zone and utility service territory modeled in this study (eight combinations). The tables illustrate the estimated share of housing in each region in 2020; these shares may change slightly over time as new housing is constructed in different parts of the state. These estimated shares are used to weight the results of the building simulations to come up with estimates of total impacts from residential low-rise building electrification. The data for Table 2-1 and Table 2-2 are derived from the estimated housing shares from the California PATHWAYS model (as illustrated in Figure 2-2) and a geographic mapping to climate zone and utility.

Table 2-1. Share of low-rise residential existing housing (as of 2020) assumed by climate zone and utility in the modeled study area

Climate Zone	Major City	Utility	Retrofits	
			Single Family	Low-rise Multifamily
CZ03	San Francisco	PG&E	17%	4%
CZ04	San Jose	PG&E	8%	2%
CZ12	Sacramento	SMUD	7%	2%
CZ06	Coastal LA	SCE	10%	3%
CZ06	Coastal LA	LADWP	2%	1%
CZ09	Downtown LA	SCE	12%	3%
CZ09	Downtown LA	LADWP	13%	3%
CZ10	Riverside	SCE	11%	3%
		Total	**80%**	**20%**

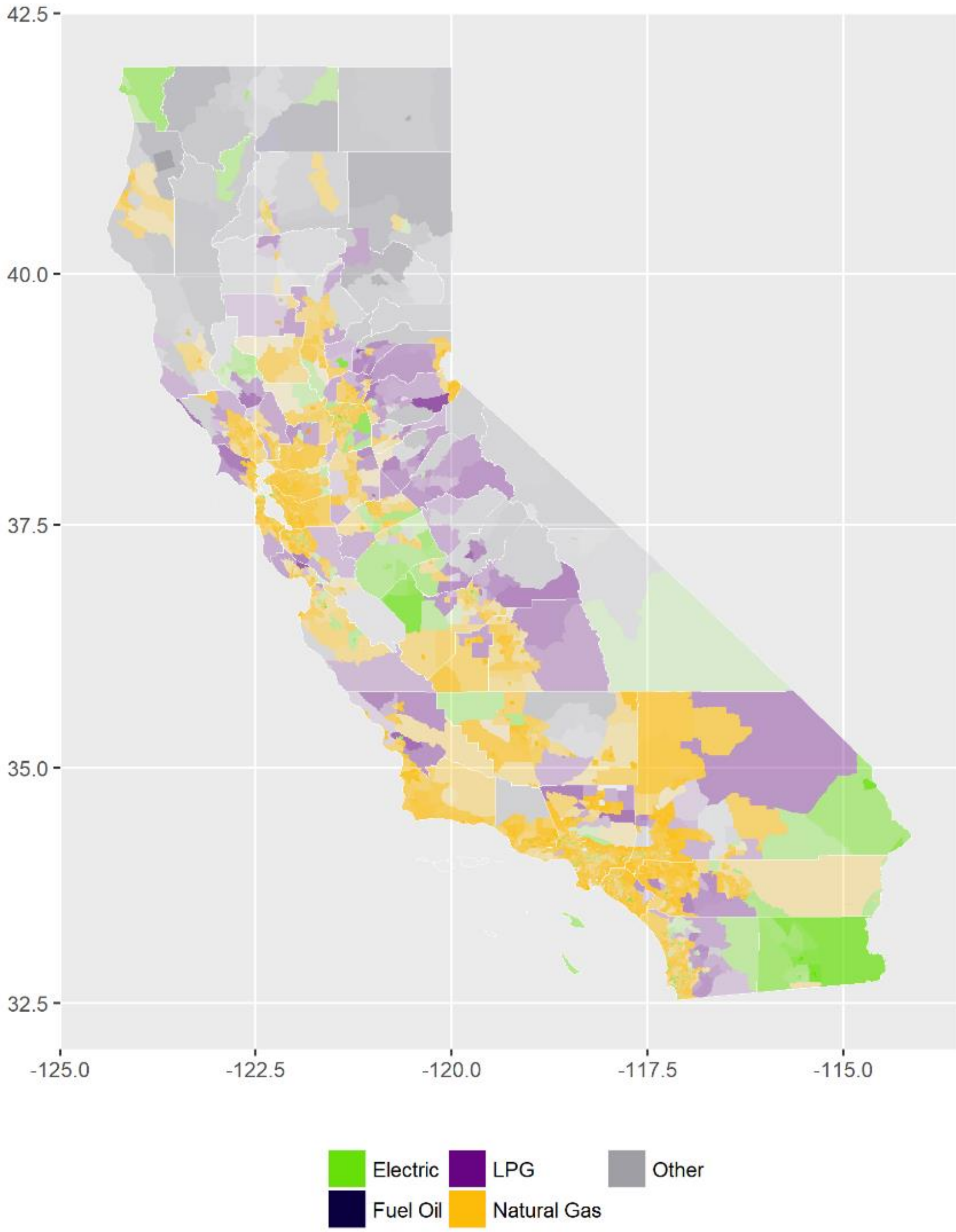
Table 2-2. Share of low-rise residential new construction housing (as of 2020) assumed by climate zone and utility in the modeled study area

Climate Zone	Major City	Utility	New Construction Single Family	New Construction Low-rise Multifamily
CZ03	San Francisco	PG&E	14%	9%
CZ04	San Jose	PG&E	6%	4%
CZ12	Sacramento	SMUD	6%	4%
CZ06	Coastal LA	SCE	7%	5%
CZ06	Coastal LA	LADWP	1%	1%
CZ09	Downtown LA	SCE	8%	5%
CZ09	Downtown LA	LADWP	9%	6%
CZ10	Riverside	SCE	9%	6%
		Total	**61%**	**39%**

2.2.2 APPLIANCE STOCK

The existing fuel mix and appliance population in California homes also provides a starting point for analysis. Most urbanized areas in California are predominantly natural gas heating, with electric heating (typically cheaper electric resistance heating) and propane (Liquefied Petroleum Gas, or LPG) in many rural areas (Figure 2-3). Overall, 86% of single family homes were estimated to use natural gas as their primary heating fuel in 2009, with a somewhat lower proportion in multifamily homes, particularly high-rise apartments (Table 2-3). This data is used to populate the 2015 PATHWAYS equipment stock and when estimating statewide impacts (except for SMUD, where utility-specific data indicated a higher prevalence of electric resistance space and water heating).

Figure 2-3: Residential Space Heating Fuel Market Share in California



Source: Authors' visualization. Data from the American Community Survey (2016). Only the plurality heating fuel is shown in each geographic region.

Table 2-3: Heating Fuel Prevalence by Housing Type in California[24]

Fuel	Single Family Detached	Townhouse	2-4 Unit Apartment	5+ Unit Apartment	Mobile Home
Electric (Resistance)	5%	13%	19%	30%	4%
Electric (Heat Pump)	2%	3%	3%	5%	4%
Natural Gas	86%	78%	69%	53%	73%
LPG	3%	1%	1%	1%	8%
No central space heating	4%	5%	8%	11%	11%

These building types are mapped to the categories used elsewhere in this report. Single family detached are single family homes. Townhouses and 2 to 4 unit apartments are grouped together as "Low-rise Multifamily". Mobile homes and 5+ unit apartment buildings (high-rise multi-family) are not considered in this report.

The prevalence of air conditioning also indirectly plays a key role in assessing the potential for building electrification, as heat pumps have a similar design and building footprint to central air conditioners, and can provide both cooling and heating functionality. The Residential Appliance Saturation Study (RASS) provided data on air conditioning prevalence by home type and climate zone.[25] Overall, it estimated that 54% of low-rise homes in California were equipped with central air conditioning and another 14% with room conditioning, with a greater proportion of central air conditioning in single family and in warmer climates in Southern California and inland in the Central Valley. The 2009 RASS showed a clear trend towards increasing central air conditioning prevalence in newer home vintages, with over 90% of new single family homes including central air conditioning statewide post-2000, but this trend was not explicitly modeled in this study.[26]

As California temperatures continue to warm due to climate change[27], it is possible that more people will adopt air conditioning to remain comfortable and avoid adverse health impacts with heat stress. This study does not take into account the fact that the AC saturation rate may continue to increase in California

[24] These data were based on the 2003 California Residential Appliance Saturation Study (RASS) (KEMA-XENERGY, Itron, and RoperASW 2004); heating fuel prevalence showed little change in the 2009 version (Palmgren et al. 2010).
[25] These data were from the 2003 RASS (see above).
[26] Data available from **https://webtools.dnvgl.com/RASS2009/Default.aspx?tabid=0**. Across all home types statewide, over 80% of new homes included central air conditioning after 2000. However, large regional variation remained, which much higher prevalence of new homes lacking central air conditioning in climate zones 3 and 5.
[27] See Pierce, Kalansky, and Cayan (2018).

over time, which could also make heat pump HVAC systems economically attractive to a larger number of households in the state.

2.3 Building Simulations and End Use Technologies

2.3.1 BUILDING SIMULATION TOOLS AND ASSUMPTIONS

Building simulations and hourly energy consumption

The hourly energy consumption of natural gas and electric technologies in homes was evaluated using industry-standard building simulation tools. Two building types were evaluated: single family (SF) and low-rise multifamily (LRMF). For each of these building types, a base case mixed-fuel home was modeled with natural gas providing space heating, water heating, cooking and clothes drying. This base case was compared to an upgraded all-electric home, with gas appliances converted to electric appliances.

Frontier Energy used the National Renewable Energy Laboratory's (NREL's) BEopt software and the Department of Energy's EnergyPlus simulation engine to develop the energy models. Modeling assumptions were mostly based on the 2014 Building America House Simulation Protocols[28], with a few exceptions. Water heater hourly draw profiles and lighting energy use reflect the most current algorithms and data incorporated in the 2016 and 2019 CBECC-Res software, which is used to demonstrate compliance with the Title 24, Part 6 energy code. This is documented in the 2016 Residential Alternative Calculation Method Reference Manual[29]. Certain modeling capabilities desired for this analysis were not available within BEopt, and therefore the energy model input files were exported and additional edits were made using EnergyPlus before running the simulations. EnergyPlus was used directly to apply the

[28] See **https://www.energy.gov/sites/prod/files/2014/03/f13/house_simulation_protocols_2014.pdf**
[29] See **https://www.energy.ca.gov/2015publications/CEC-400-2015-024/CEC-400-2015-024-CMF-REV3.pdf**

California water heater draw profiles and also make adjustments to other water heating inputs that could not be done in BEopt.

In all building simulations, weather files were based on the California Energy Commission's Title 24 typical meteorological year data. The key modification from the Title 24 building specifications was a modification of the heating and cooling set-point schedules, to conform with observed California data. The Title 24 schedules include uncharacteristic setbacks. The project team settled on a heating and cooling setback schedule based on a review of relevant literature, including California Nest data. For more details about the thermostat set point assumptions and other building simulation parameters see Appendix B: Building Simulation Descriptions.

2.3.2 BUILDING TYPES AND CLIMATE ZONES MODELED

Two building types are modeled across six California climate zones (see Table 2-4 and Figure 2-4). The assumptions about each home type are described below. We designed each case as a comparison between a mixed fuel home, with natural gas space heating, water heating, cooking, and clothes drying, and an all-electric home.

We attempted to compare options with similar levels of comfort and aesthetic characteristics whenever possible in order to provide the most fair comparison. For instance, we only compared retrofit homes in which air conditioning would be found in the mixed fuel home, for comparison with an electric home containing an HVAC heat pump providing cooling services. For new construction, we excluded technology options like packaged terminal heat pumps (PTHPs) that may be inexpensive but are seen as less aesthetically desirable.

1) Single family homes are assumed to be a one- or two-story detached home, with the square footage of the home depending on the vintage. The older pre-1978 vintage homes are assumed to be constructed before the California building code went into effect and include poor levels of building insulation and single pane windows. These homes are assumed to be single-story, two-bedroom, 1,400 square foot homes. The 1990's vintage homes are assumed to be single story, three-bedroom, 2,100 square feet homes built to comply with the 1992 building code, with minimal building insulation and double-pane windows. New construction homes are the largest homes modeled, at 2,700 square feet with two floors and four bedrooms. New construction homes are designed to meet the 2019 Title 24 building code requirements, including the requirements for new rooftop solar PV (a 3 kW solar array per home is assumed). New construction homes are assumed to install the same size rooftop solar panel in both the gas baseline and all-electric home, and as a result the rooftop solar has a relatively minor impact on the relative bill savings between these two options. The 2,100 square foot (1990's vintage) and the 2,700 square foot (new construction) homes are based on the California Energy Commission's single family prototypes used in the Title 24, Part 6 development process.

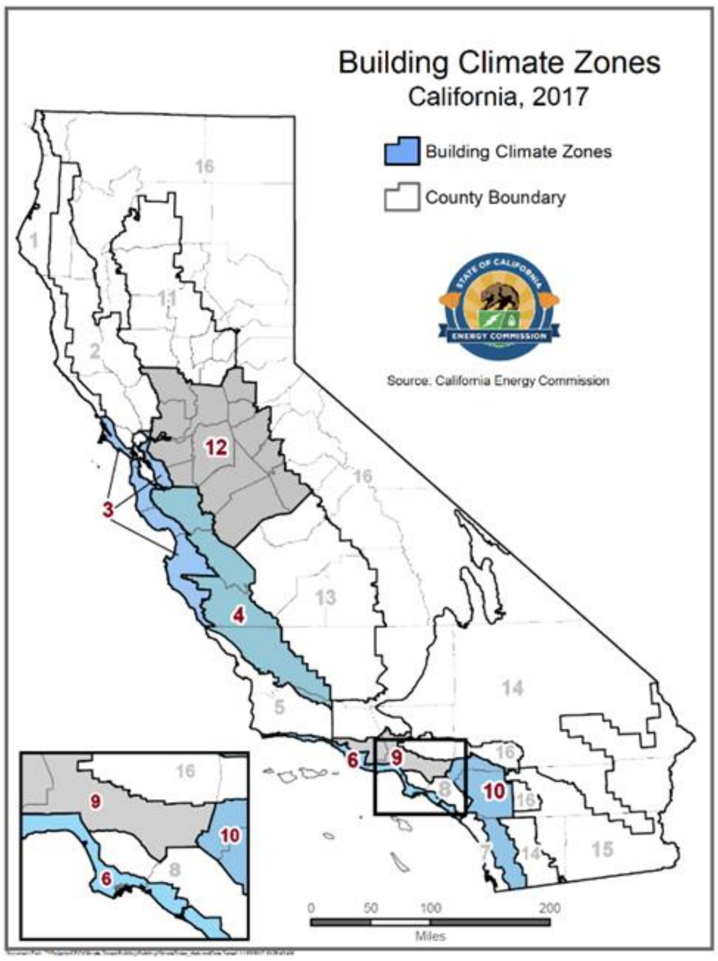
2) Low-rise multifamily (LRMF) homes are assumed to be two-story apartment buildings with six to eight units, depending on the building vintage. Like the single family homes, the LRMF new construction buildings have minimal insulation for the older vintage construction, meet the 1992 building code requirements for the 1990's vintage homes, and achieve the 2019 Title 24 building code requirements for new construction, including the use of rooftop solar PV (1.75 kW per unit is assumed). New construction homes are assumed to install the same size rooftop solar panel in both the gas baseline and all-electric home, and as a result the rooftop solar has a relatively minor impact on the relative bill savings between these two options. The pre-1978 vintage and the new construction building prototypes both include four one-bedroom, 780 square foot units, and four two-bedroom 960 square foot units. The 1990s vintage building includes six three-bedroom, 1,500 square foot units. The pre-1978 and the new construction vintage homes are based on the California Energy Commission's multifamily prototypes used in the Title 24, Part 6 development process.

Table 2-4 Modeled building types and vintages

	Single-Family	Low-Rise Multifamily
Retrofit (Pre-1978) (No insulation, single pane windows)	**1,400 sf**	6,660 sf 8 units (**780 sf/unit + 960 sf/unit**)
Retrofit (1990s) (T24 building code 1992 construction)	**2,100 sf**	9,000 sf 6 units (**1500 sf/unit**)
New Construction (2019 T24 building code)	**2,700 sf**	6,660 sf 8 units (**780 sf/unit + 960 sf/unit**)

For each of the six building types evaluated (as described in Table 2-4 above), building simulations are performed across six California climate zones. The climate zones were selected to represent a sample of the largest population centers in California across the service territories of the participating utilities (SCE, SMUD and LADWP), with the inclusion of two Northern California climate zones in PG&E's service territory for completeness. Overall, these six climate zones represent about 50% of the state's households, covering the regions around: San Francisco, San Jose, Sacramento, Coastal Los Angeles, Downtown Los Angeles and Riverside. Data from the Residential Appliance Saturation Survey suggest that 62% of the households in the six climate zones we studied have central or room air conditioning in our study area, compared to 68% statewide, suggesting that our study area is moderately representative of the statewide air conditioning saturation rate. We estimate that the climate zones included in this study are broadly representative of about 90% of the state's households. An assessment of building electrification for the remaining 13% of the state's households, largely rural, represents a potential area for further study.[30]

Figure 2-4. California's Building Climate Zones, six study area climate zones evaluated are shaded in blue and grey



[30] Poorly covered climate zones which may be quite dis-similar to those modeled include the climate zones 1 and 2 along the northern coast, the northernmost Central Valley in climate zone 11, the mountainous climate zone 16, and the southeastern desert climate zones 14 and 15. We note that many of these climate zones include rural households that lack natural gas infrastructure and use expensive propane or electric resistance heating (Figure 2-3), so may be good candidates for heat pump retrofits as shown in previous studies.

For each climate zone, the electric and natural gas residential rates for the corresponding major utilities are evaluated in the customer bill savings calculations: PG&E, SMUD, SCE and LADWP electric rates, and PG&E and SoCalGas natural gas rates are applied, as shown in Table 2-5 below.

Table 2-5 Electric and gas utilities in the six climate zones

Building Climate Zone	Major City	Utility Rates Evaluated	
		Electric	Gas
CZ03	San Francisco	PG&E	PG&E
CZ04	San Jose	PG&E	PG&E
CZ12	Sacramento	SMUD	PG&E
CZ06	Coastal LA	SCE / LADWP	SoCalGas
CZ09	Downtown LA	SCE / LADWP	SoCalGas
CZ10	Riverside	SCE	SoCalGas

2.4 Upfront equipment costs and efficiencies

For this study, we found that existing data sources on natural gas and electric equipment costs were lacking in key respects. The existing data sources that we evaluated generally did not include estimates of the labor and installation costs of building electrification retrofits, focusing only on equipment costs. For example, the U.S. National Energy Modeling System (NEMS) data assumes a "like for like" replacement of equipment and does not include estimates of retrofit costs. In addition, some data sets did not include a comprehensive set of cost data for a range of natural gas and electric technologies.

Given the need for a comprehensive and internally-consistent set of installed equipment cost data across a range of building types and regions of California, we decided to create new estimates of installed building equipment technology costs using a professional cost estimator from AECOM. Of course, no single point cost estimate of installed building equipment will be applicable across all buildings, even if those cost are specific to a given building type and geography. Buildings are heterogenous; in particular, retrofit and equipment installation costs vary based on many factors.

The cost-estimation approach relies on a combination of published equipment costs and market and professional experience. By creating this bottom-up estimate of installed capital costs using the same cost estimator, we hope that we have at least captured the most common sets of cost drivers in an internally consistent way.

The all-in, installed capital costs of electric equipment are compared to the cost of natural gas equipment using cost estimates. Capital costs, including installation, labor and retrofit costs were developed using California-specific information about labor rates and standard industry mark-ups. In the case of heat pump HVAC systems, which provide both heating and cooling, the costs of the electric heat pump are compared to the cost of a natural gas furnace plus an air conditioner, in regions of the state where air conditioning is prevalent. In retrofit situations, the electric heat pump HVAC system is assumed to replace a gas furnace, plus a portion of the cost of a new air conditioner. This adjustment is made to reflect the fact that there is still some useful economic life remaining in an air conditioner if it is replaced when the gas furnace fails. The guiding principal here is to minimize early retirement of equipment where possible – generally assuming only “replace-on-burnout” in retrofit situations, except for the air conditioner which is replaced upon burnout of the gas furnace.

We assume that homes that do not currently have air conditioning (primarily those in the San Francisco/Climate Zone 3, in this study), will not adopt air conditioning in gas-fueled homes. However, existing homes that currently have window AC units are assumed to upgrade to a central AC system when they replace the HVAC system. This assumption attempts to ensure that we are comparing similar levels of thermal comfort in both the gas-fueled and electric homes in areas where air conditioning is commonly needed.

Capital costs are estimated for heat pump HVAC systems, heat pump water heaters, electric resistance and induction stoves and electric resistance and heat pump clothes dryers separately. For all-electric new construction homes, the avoided cost of natural gas infrastructure (both in-home and for interconnections to the utility) is included in our cost model. The avoided in-home natural gas piping infrastructure is reflected in the equipment capital cost estimates developed by AECOM.

An additional cost saving is applied separately based on an estimate of the avoided natural gas piping cost associated with the service and meter connection. In practice, these avoided costs will be highly site-specific and could vary widely depending on the size and location of the housing project. The estimated avoided costs of natural gas infrastructure and interconnection to the utility (outside of the avoided gas piping in the building itself) are based on estimates from the draft 2020 California Title 24 Building Reach Code [31] and include:

+ Single family residence: $6,000
+ LRMF: $6,000 (cost is shared by 6-8 units, resulting in $750 or $1,000 per household)

Gas interconnection costs will vary greatly depending on the location of the building, making it difficult to come up with a single, central estimate. If anything, these avoided gas infrastructure costs may represent conservative estimates. However, it is important to note that in this study, the avoided gas infrastructure cost savings within the building itself are included in the equipment capital cost estimates. This study does

[31] Based on estimates from, "PG&E Residential Building Gas Service Installation Costs" dated January 28, 2019.

not attempt to estimate the avoided societal costs of gas interconnections for new construction, which are shared among all gas ratepayers and would not be a cost or benefit to individual customers.

In retrofit homes moving from gas to electric end uses, the individual replacement of one end use or appliance is not assumed to trigger the need for a complete electrical panel upgrade. Pre-1978 vintage homes are assumed to trigger the incremental cost of a panel upgrade to 200A when both the HVAC and domestic hot water systems are electrified at the same time. The following panel upgrade costs are applied[32,33]:

- Single family: $4,256
- Low-rise multifamily: $2,744

Hourly labor rates vary by region of the state and are estimated based on all-in costs for experienced and licensed contractors. These labor rates vary from $65/hour to $95/hour depending on the region. The total cost estimates also reflect a mark-up for overhead, which varies between 15% to 20% depending on the region of the state. Design and engineering costs are 10% of the project cost. Permit, testing and inspection costs are 1.25% of project costs, while contractor profit and market factors are used to reflect local market conditions in some markets and vary from 0% in Sacramento and Riverside to 8% in San Francisco.

To illustrate the categories included in the capital cost estimates for each technology, an example is provided below for a 1990s vintage single family home that retrofits a gas furnace to an electric HVAC heat pump.

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[32] See the City of Palo Alto 2019 Title 24 Energy Reach Code Cost Effectiveness Analysis: **https://cityofpaloalto.org/civicax/filebank/documents/66742**

[33] See the Palo Alto Electrification Final Report: **https://www.cityofpaloalto.org/civicax/filebank/documents/55069**

Figure 2-5. Example of installed equipment capital cost data developed for this analysis: Singe family HVAC heat pump retrofit, 1990s vintage, Climate Zone 6

Demolition		
Remove existing furnace		
Labor		680
Disposal		500
		1,180
Installation		
Furnace		*Included in heat pump*
New Furnace, equipment price		
Heating included in split system heat pump		
Miscellaneous supplies		
Labor		
Air Conditioner		
New Air Conditioner, equipment price	$	5,400
Ducted split heat pump AHU in attic, 3-ton 18 SEER/14 EER, 10 HSPF, two-	$	-
Concrete pad, precast	$	100
Refrigerant piping and refrigerant	$	400
Miscellaneous supplies	$	400
Labor	$	1,360
Controls		
Thermostat & wiring	$	400
Gas and Electrical Supply		
New electrical circuits to equipment	$	190
Panel and main service modification		*Not required*
Gas supply piping		*Not required*
Labor	$	340
Ductwork modifications	$	-
Miscellaneous supplies	$	250
Labor	$	680
	$	9,520
Subtotal	$	10,700
	$	-
General Conditions and Overhead	$	1,605
Design and Engineering	$	1,231
Permit, testing and inspection	$	169
Contractor Profit/Market Factor	$	274
Recommended Budget	$	13,979

2.4.1 TECHNOLOGIES MODELED

Existing mechanical system types are selected to represent typical construction practices for each building type and vintage. In the building models used in this study, appliances are replaced at the end of their useful life ("replace on burnout") and replaced with either a comparable electric technology or a comparable gas technology. The electric upgrade case applies the electric technology that best complements the existing conditions while considering cost, technical feasibility, market feasibility, and occupant acceptance. In most cases, the gas upgrade assumes replacement with the same type of equipment as is existing. All applicable building codes are assumed to be met in both the electric and gas upgrade cases.

2.4.1.1 Heating, Ventilation and Air Conditioning (HVAC) Systems

In the gas-fueled homes modeled, the HVAC system consists of a natural gas furnace and an air conditioning unit. The size and type of the gas furnace and air conditioner vary based on the home type and the climate zone. The natural gas baseline home is assumed to meet the code minimum requirements for HVAC equipment in 2018. Homes with window air conditioning are assumed to be retrofitted to central air conditioning in order to ensure a comparable level of home comfort with the electric heat pump alternative. Overall, the building simulations suggest that in the California climate zones modeled here, HVAC heat pumps may perform better than their rated efficiencies, due to the relatively mild climate compared to the efficiency rating test conditions. Below we present the rated efficiencies of the equipment modeled; the "achieved" efficiencies vary by home type and climate zone and are generally higher.

Three types of electric air source heat pump HVAC systems are evaluated:

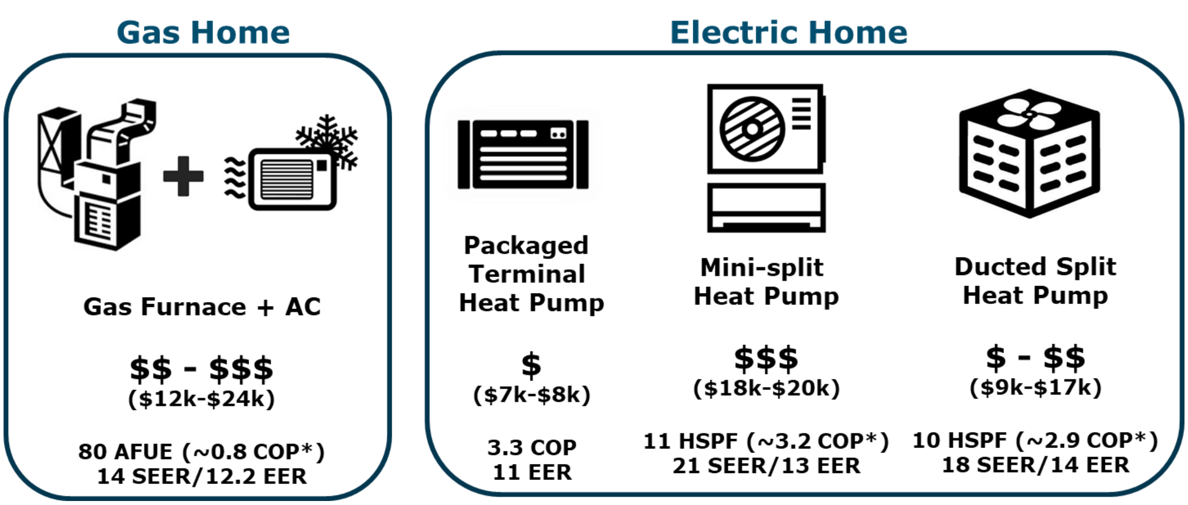
+ **Packaged terminal heat pumps:** These are self-conditioned units which can provide both space heating and cooling. They are often found in hotels but are increasingly considered as low-cost options for small apartments and condos. Packaged terminal heat pumps (PTHPs) are generally only appropriate for smaller homes and are modeled here with a COP of 3.3.

+ **Mini-split heat pumps:** These heat pumps have an outdoor compressor/condenser and one or more indoor fan coil units. Ductless mini-split heat pumps can be installed in homes without ducts, which can make them good options for some retrofit situations. Mini-split heat pumps utilize a variable speed compressor and can achieve very high efficiencies. The base case modeled efficiency in this study is an HSPF of 11 (or a rated COP of 3.2, although actual performance will vary by climate and use patterns).

+ **Ducted split heat pumps:** A ducted split heat pump also has an outdoor compressor/condenser, but only one indoor air handling unit which pushes air throughout the home via ducts, in the same way that a central air conditioning system and furnace would. The base case modeled efficiency in this study is an HSPF of 10 (or a rated COP of 2.9, although actual performance will vary by climate and use patterns).

The various HVAC systems used in the homes modeled are summarized in Figure 2-6.

Figure 2-6 Modeled gas and electric HVAC systems: technology, price range and efficiency



Ranges reflect the range of prices across climate zones as a result of labor cost differences.

In addition to the “common high-efficiency” products modeled in the base case, we also evaluate the performance of a “best-in-class” product and an “emerging technology” product for the ducted split HVAC heat pumps and mini-split HVAC heat pumps. The Best-In-Class product represents the highest efficiency available in today’s California marketplace. The Emerging Technology product represents expected technology advances in future products.

Table 2-6. and Table 2-7: Low-rise describe the rated efficiencies applied in this analysis to HVAC equipment for the standard product as well as the two higher-efficiency tiers.

Table 2-6. Single family HVAC New Construction Efficiencies

		Seasonal AHRI Ratings		
Ducted split air source heat pump	**# Speeds**	**SEER**	**EER**	**HSPF**
Common High Eff Product	2	18	14	10
Best-In-Class Product	variable	21	15	13
Emerging Tech Product	variable	25	18	16

Table 2-7: Low-rise Multifamily HVAC New Construction Efficiencies

		Seasonal AHRI Ratings		
Mini-split heat pump	**# Speeds**	**SEER**	**EER**	**HSPF**
Common High Eff Product	variable	21	13	11
Best-In-Class Product	variable	30	15	14
Emerging Tech Product	variable	36	18	17

Best-In-Class performance assumptions are based on products in the Air-Conditioning, Heating, & Refrigeration Institute's (AHRI's) certification directory[34] and are selected either to match those products with the highest available HSPF or go slightly beyond. For the Emerging Technology option, the project team researched trends in system performance and technology.

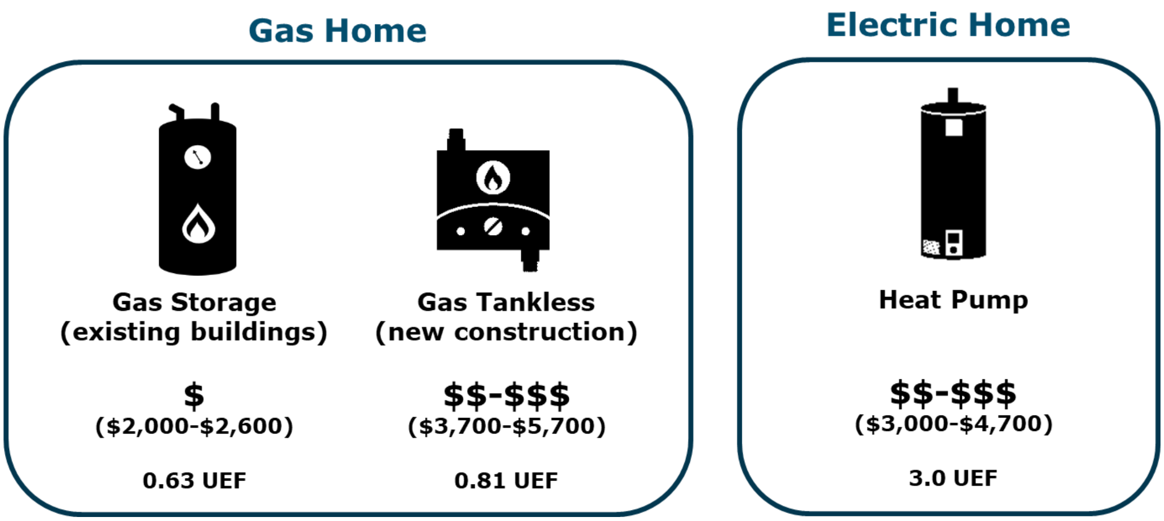
An IEA study from 2011[35] stated that heat pump COP performance (for both cooling and heating) is expected to increase by 20% in 2020 and 50% in 2030. Assuming the 2020 target has been met, this translates to an additional 25% increase moving to 2030. For this analysis the Emerging Technology performance was assumed to be 20% better than the Best-In-Class, applying a slightly more conservative improvement factor than the IEA study to better represent the next 5 years.

2.4.1.2 Domestic Hot Water (DHW)

In existing, natural gas-fueled homes, the base case domestic hot water system is assumed to be a code-minimum gas storage water heater with a uniform energy factor (UEF) of 0.63. In new construction gas-fueled homes, consistent with the requirements of the California Title 24 building code, gas tankless water heaters are assumed, with efficiencies of UEF 0.81. In the electric retrofit and electric new construction alternatives, heat pump water heaters are evaluated, with a base case efficiency of UEF 3.0.

[34] See https://www.ahridirectory.org
[35] See https://webstore.iea.org/technology-roadmap-energy-efficient-buildings-heating-and-cooling-equipment

Figure 2-7 Modeled gas and electric water heating systems: technology, price range and efficiency



Ranges reflect the range of prices across climate zones as a result of labor cost differences.

Higher efficiency heat pump water heaters are evaluated in a sensitivity analysis, using a "best-in-class" efficiency of 3.4 UEF, and an "emerging technology" UEF of 4.1. Table 2-8. describes the rated efficiencies applied in this analysis to water heaters for the standard product as well as the two higher-efficiency tiers.

Table 2-8. Heat Pump Water Heater Efficiencies

	Rated Efficiencies	
Technology Class	**UEF**	**COP**
Common High Efficiency Product	3.0	3.5
Best-In-Class Product	3.4	4.3
Emerging Tech Product	4.1	5.0

Best-In-Class performance was based on the Sanden heat pump water heater.[36] For this performance category, the Sanden COP was reduced by 15% relative to the rated value of 5.0 to better align with results from the CBECC-Res software, which was used to demonstrate compliance with the Title 24, Part 6 energy code. The Emerging Technology performance was based on the Sanden product without any derating.

Flexible water heating sensitivity assumptions

Water heater production can be optimized to save energy while still meeting service demand, thanks to the heat storage capability of water. Smart control technology can enable water heaters to shift electricity demands to avoid the high electric rates under a time-of-use (TOU) rate schedule. We perform a flexible water heating sensitivity analysis to evaluate the impact of this technology on consumer economics, assuming that the heat pump water heater runs at minimal power during the peak hours, and is able to shift all heating demands to hours before the highest priced TOU period. For the purposes of this sensitivity we assume that energy demands are shifted prior to the peak TOU period rather than after the peak TOU period – however, since off-peak TOU rates are generally symmetrical before and after the peak TOU rate, this assumption does not affect the consumer cost results. Other research has demonstrated that the use of flexible heat pump water heaters is a feasible technology option, and can provide customers with benefits in the context of Title 24 building code compliance.[37]

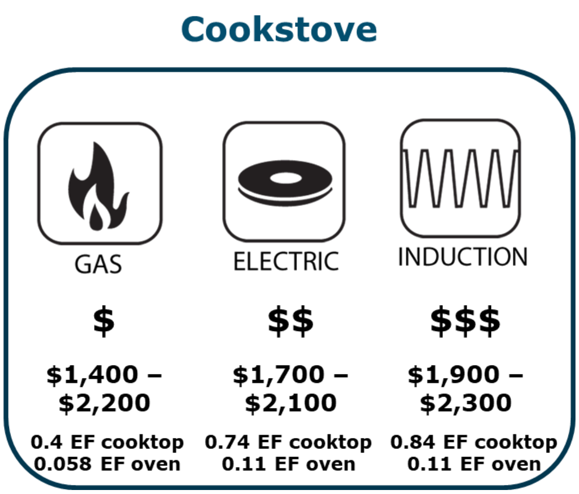
2.4.1.3 Cooking

Natural gas stoves are compared on a cost and efficiency basis to electric resistance stoves, which are assumed in low-rise multifamily homes, and electric induction stoves, which are assumed for single family homes. In practice, an induction or electric resistance stove could be installed in any type of home. These

[36] See https://www.sandenwaterheater.com/products/
[37] See Grant and Huestis (2018).

assumptions reflect the fact that electric resistance stoves are generally considered a less high-end product than induction stoves.

Figure 2-8 Modeled gas, electric and induction cookstoves: price range and efficiency

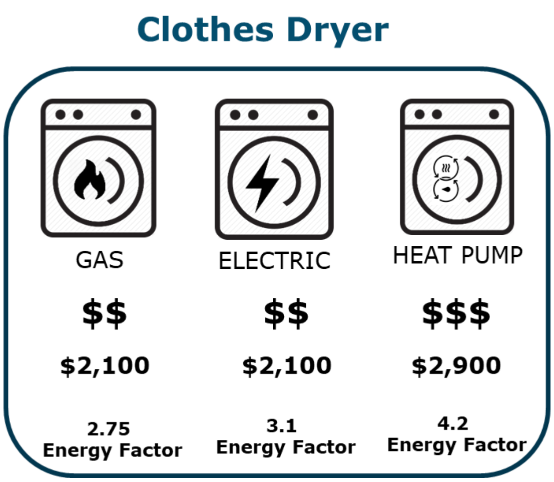


Ranges reflect the range of prices across climate zones as a result of labor cost differences.

2.4.1.4 Clothes Drying

The cost and performance of natural gas clothes dryers are compared to electric resistance clothes dryers in low-rise multifamily homes, and to electric heat pump clothes dryers in single family homes. In practice, an electric resistance or heat pump clothes dryer could be installed in any type of home, but this assumption is applied because heat pump clothes dryers are generally a higher cost product, and so are more likely to be found in the single family homes modeled.

Figure 2-9 Modeled gas, electric and heat pump clothes dryers: price range and efficiency



2.4.1.5 All-electric New Construction

For all-electric new construction homes, the avoided cost of natural gas infrastructure (both in-home and for interconnections to the utility) is included in our cost model.

In all-electric homes, regardless of whether the home is new construction or retrofit, the customer bill savings are also adjusted, to reflect the fact that the customer is no longer obligated to pay any of the fixed fees associated with the natural gas rates. The fixed fees on the natural gas rate schedules are not avoided for homes that continue to have one or more natural gas appliances or end uses.

2.5 Customer Costs and Savings

2.5.1 ELECTRICITY AND NATURAL GAS RETAIL RATES: CURRENT AND FUTURE RATE ASSUMPTIONS

To calculate the consumer bill impacts of electrification, we use the hourly energy consumption data from the building simulation results and apply the gas and electric rates appropriate for each utility service area to come up with an estimated cost of consumer utility bills. Both categories of rates are assumed to start at the 2018 rate schedules and escalate over time, using the best information about near-term rate escalation. Escalation of natural gas rates between 2019 and 2022 is based on the currently filed General Rate Cases (GRCs) for PG&E and SCG. The GRC for SCG, if approved in full, implies a cumulative 32% real increase in residential gas rates between 2018 and 2022.[38] During this same time period, PG&E rates would likely increase by a cumulative 6% real based on its filed GRC.[39] From 2023 through 2025, gas rates are assumed to escalate at 4% real per year, corresponding to historical rate increases between 2013 and 2018.[40] Escalation of electricity rates from 2019 through 2025 is assumed to be 2% per year above inflation, based on estimates provided by the electric utilities participating in this study, reflecting the need for transmission and distribution upgrades as well as compliance with SB 100.

After 2025, both natural gas and electric rates are assumed to escalate a more conservative 1% real escalation for long-term rate trajectories beginning in 2026 - 2050. This 1% escalation is based on the Handy-Whitman Index for construction between 1971 and 2016 and does not presuppose specific new

[38] See **https://www.socalgas.com/documents/regulatory/bill-inserts/FINAL_Printer_Proof_SCGC_GRC_Reg.pdf** for the SCG 2019 GRC, and Ex. 46 table ISC-03 and Ex. 44 "Summary". We assumed no changes in cost allocation from 2019 through 2022, so that the change in total revenue requirement is directly proportional to the change in residential rates.

[39] See **https://www.pge.com/pge_global/common/pdfs/about-pge/company-information/regulation/2020-General-Rate-Case-Summary.pdf** for the PG&E gas 2020 GRC, Ex. 12, Table 10-2; Ex. 11, Table 2-5; and Ex. 17, Table 17A-1. We assumed no changes in cost allocation from 2019 through 2022, so that the change in total revenue requirement is directly proportional to the change in residential rates.

[40] The historical natural gas rate increases are calculated based on the average residential retail gas price in California reported by the Energy Information Administration (EIA). **https://www.eia.gov/dnav/ng/hist/n3010ca3A.htm**

investments, changes in load and gas throughput, or other measures associated with complying with California's climate policy goals.[41]

In addition to the 1% per year real escalation rate, we also assume a rising carbon price trajectory through 2030. This carbon price trajectory is based on the 2017 CEC IEPR "High" price scenario[42], reaching $84 (in 2018$) in 2030. The carbon price is used to determine a carbon price adder relative to today's rates, which are assumed to already reflect the current market price for carbon. We chose the CEC high carbon price scenario because of the key role of cap-and-trade policy in meeting California's 2030 climate goal, based on the adopted 2017 CARB Scoping Plan.[43]

In this analysis, we have not attempted to forecast how the cost of wildfires may affect future electricity rates, nor have we tried to estimate how the cost of meeting the state's long-term climate goals will affect rates. Renewable natural gas and electrification are both likely to increase natural gas rates, which could lead to more favorable economics for electrification than are shown here.

To address the sensitivity of our results to higher near-term electric rate increases, we include a sensitivity analysis where electric rates increase at the same rate as natural gas rates. The rate escalation schedule from SoCalGas (showing a cumulative 32% increase above inflation from 2018 through 2022) is applied to the electric rates for SCE, PG&E, and LADWP, and the rate escalation schedule from PG&E's gas rates (showing a cumulative 6% increase above inflation from 2018 through 2022) is applied to the electric rates for SMUD. PG&E's electric rates are included in the first group due to the higher estimated potential for

[41] This escalation rate is likely conservative, depending on how California implements its building decarbonization strategy. Mahone et al. (2018) showed complying with 80 x 50 requires large declines in gas throughput (i.e., from gas efficiency and building electrification), substitution of expensive renewable natural gas for fossil natural gas, or both; this would tend to exert large upwards pressure on volumetric gas rates. Furthermore, Governor Brown's recent Executive Order B-55-18, established a carbon neutrality target for 2045, which is more strict than 80 x 50. ("80 x 50" refers to the state's existing goal of an 80% reduction in GHG emissions below 1990 levels by 2050.) However, complying with SB 100 and other state policy goals may also increase electricity rates beyond that modeled here as well.

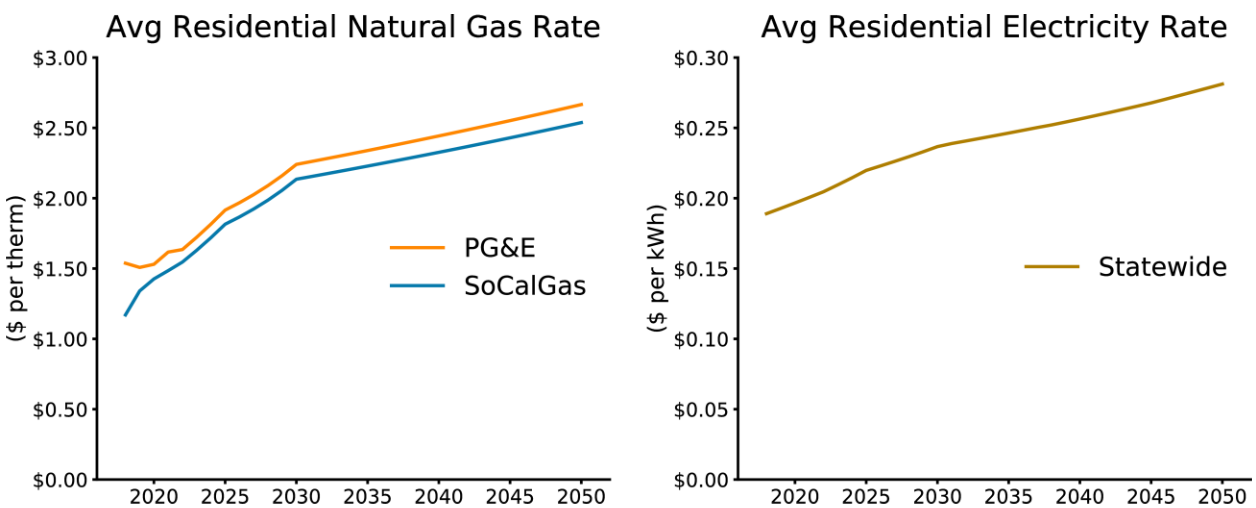
[42] https://efiling.energy.ca.gov/GetDocument.aspx?tn=216271

[43] https://www.arb.ca.gov/cc/scopingplan/scoping_plan_2017.pdf

near-term rate increases. The results of this sensitivity analysis are presented alongside the main results in the Consumer Bill Impacts Section 3.3.5 and the Lifecycle Costs and Savings section 3.4.5.

The base case, or "reference" rate escalation assumptions applied in this study for electricity and gas are summarized in Figure 2-10.

Figure 2-10: Residential natural gas and electricity rates, reference scenario (real 2018$)



Rates are averaged over delivered natural gas for core customers and electricity for all end uses.

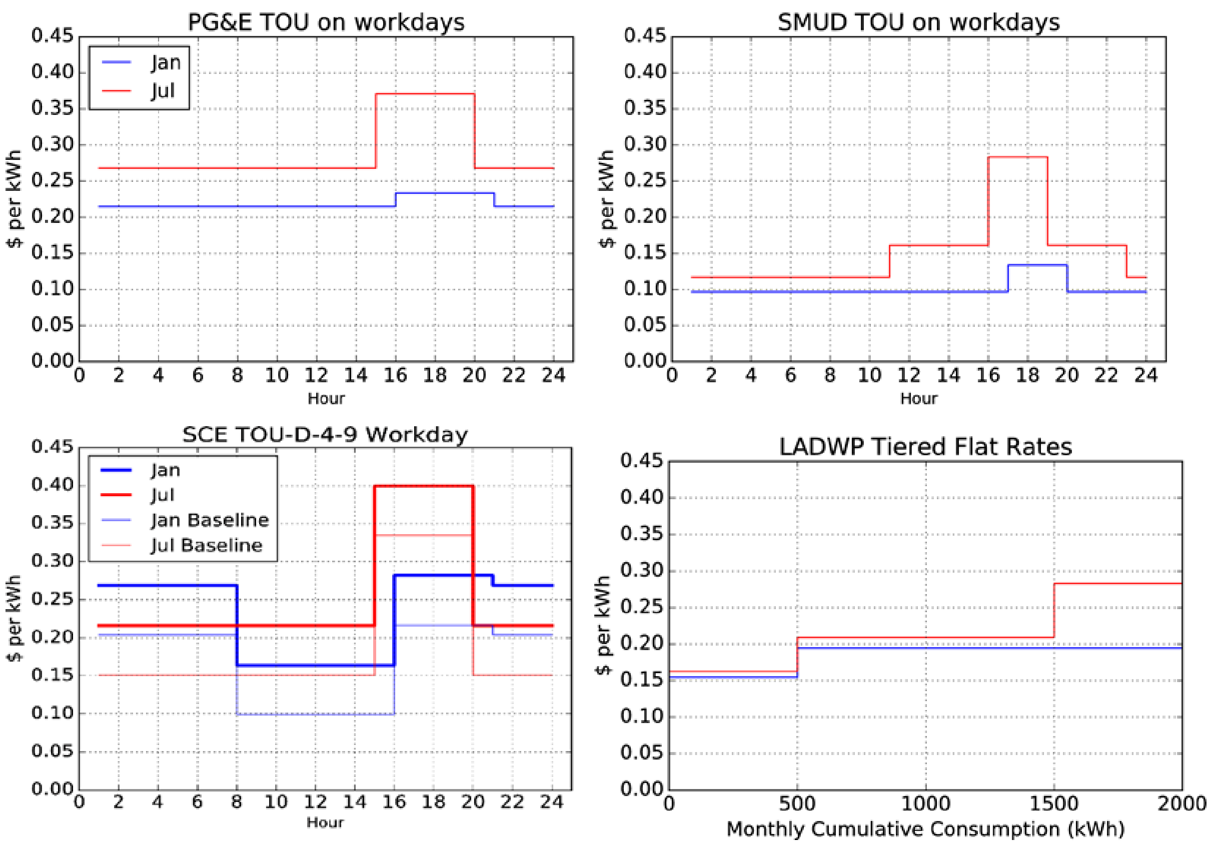
The above escalation rates are applied to 2018 residential electric and gas rate schedules for each utility to come up with future rate schedules, which are summarized in Table 2-9 and Figure 2-11. We emphasize that future rate designs and cost allocation schemes could vary substantially from today's rates. For electric rates, both the SCE TOU-D-4-9 rate (filed with the 2018 GRC) and the PG&E E-TOU OPTION B rate schedule have a 4pm-9pm peak, representing the typical peak demand of the grid after residential solar generation ramps down. These two utilities' electric rates are higher than others, peaking at $0.35-$0.40 per kWh. SMUD 1-R-TOD has the lowest rates and a much shorter period of peak rates (5pm-8pm). LADWP R-1(A) is the only tiered and flat schedule. Depending on the monthly consumption of the consumer, the LADWP rate in most cases is higher than SMUD, but lower than PG&E and SCE. The SCE TOU-D-4-9 schedule is the only one that features a highly differentiated TOU structure in winter. Furthermore, on this rate schedule, SCE credits customers (on a per-kWh basis) whose consumption is below the monthly baseline, represented by the faded line in Figure 2-11.

Residential natural gas retail rates for PG&E and SoCalGas are modeled for northern California and southern California respectively. Both rates feature a tiered structure subject to daily baselines and are subject to regional and seasonal gas price variations. The 2018 PG&E G-1 residential rate averaged $1.3 or $1.8 per therm depending on daily usage. The 2018 SoCalGas GR rate was 30% lower than PG&E, at $0.9 or $1.2 per therm on average depending on daily usage.

Table 2-9: Electric and gas rate schedules applied in this study for each utility service territory.

Utility	Electricity Rate Schedule Name
SCE	TOU-D-4-9 (TIME-OF-USE DOMESTIC) (Filed)
PG&E	E-TOU (RESIDENTIAL TIME-OF-USE) OPTION B
SMUD	1-R-TOD (RESIDENTIAL TIME-OF-DAY)
LADWP	R-1(A) (RESIDENTIAL STANDARD TIERED FLAT RATE)
Utility	**Gas Rate Schedule Name**
PG&E	RESIDENTIAL SCHEDULE G-1
SoCal Gas	RESIDENTIAL SERVICE GR

Figure 2-11: 2018 hourly electric rates for each utility service area.



Red lines represent summer rates, and blue lines represent winter rates. Southern California Edison (SCE) gives credits (per kWh base) for customers whose consumption is below its monthly baseline, indicated by the faded line in the SCE chart. Note that time shown is based on Pacific Standard Time, so the summer peak would be one hour earlier in Pacific Daylight Time.

2.5.2 LIFECYCLE COSTS AND SAVINGS

Lifecycle costs reflect the cost of ownership of an appliance, including both capital and operating costs, spread over its lifetime (maintenance costs/savings are not estimated in this study). We calculate lifecycle cost as the monthly present value of the total capital costs and bill costs of an appliance throughout its lifetime. Lifetimes of the modeled appliances are assembled from data supporting the National Energy

Modeling System, applying the average estimated lifetime in this study (see Table 2-10). A single equipment lifetime is assumed for HVAC systems (including both the air conditioning and gas furnace systems). For the all-electric home lifecycle analysis, a 30-year lifetime is assumed, consistent with the California Energy Commission's Title 24 residential building code assumptions.

We apply a 3.35% after-tax real discount rate to the annualized capital costs and bill costs. This is equivalent to an 8% nominal discount rate that reflects a typical home equity line of credit or mortgage rate that a consumer may have access to when renovating or purchasing a home.

Table 2-10: Assumed equipment lifetimes from data supporting the National Energy Modeling System (NEMS).[44]

	Equipment lifetime
Heat Pump	18
Gas Fired Furnace	
Central AC	
Gas Water Heater	13
Heat Pump Water Heater	13
Cookstove	12
Clothes Dryer	13
All-Electric Home (for bill impact calculation only)	30

2.6 Greenhouse Gas Emissions

Greenhouse gas emissions from homes include emissions from three categories: direct emissions from natural gas combustion (or other fuels, not assessed here), indirect fossil fuel combustion emissions from electricity consumption, and fugitive emissions from either methane in the natural gas system or high-

[44] See https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/appendix-a.pdf [Accessed on July 26th, 2018]

GWP refrigerants leaked from air conditioners, heat pumps, refrigerators and freezers. The methodology for calculating each of these is described below.

2.6.1 COMBUSTION EMISSIONS FROM NATURAL GAS

The emissions intensity of natural gas is modeled as that of fossil natural gas (0.053 tonnes/mmBTU-High Heating Value) when calculating GHGs. To achieve California's long-term climate goals, the emissions intensity of natural gas, and/or the total consumption of natural gas, will need to decline dramatically. However, as described in Section 2.5.1, we take a conservative approach and assume neither an increase in the cost of natural gas in the base scenario, nor a decrease in the emissions intensity of natural gas, to avoid a presumption about how the natural gas industry will comply with the state's climate goals.

2.6.2 INDIRECT FOSSIL FUEL COMBUSTION EMISSIONS FROM ELECTRICITY

For the 2030 timeframe, indirect fossil fuel combustion emissions from electricity are calculated based on hourly marginal electricity emissions rates. These emissions rates are based on the simulated performance of the Western Electricity Interconnect under a future in which California achieves a 60% RPS by 2030. For 2050, greenhouse gas emissions are calculated based on a long-run average emissions rate for electricity from the California PATHWAYS High Electrification scenario. This is a scenario in which California achieves the electricity sector goals of SB 100 by 2045 and sees high levels of energy efficiency and electrification across the building and transportation sectors. More details are found in Appendix C: Additional Methods Detail.

We do not attempt to quantify the upstream methane leakage emissions associated with natural gas-fired electricity generation. These emissions would not change our results significantly and will become negligible as California's grid becomes less reliant on natural gas due to compliance with SB 100.

2.6.3 FUGITIVE EMISSIONS OF METHANE

The national infrastructure for natural gas has leaks at many steps of the production and distribution process. These leaks have outsized impacts on the climate impacts of natural gas use, since methane, the chief component of natural gas, has a higher global warming potential (GWP) than natural gas.[45] This means that each 1% leakage of natural gas volume translates to a 9% increase in effective GHG emissions.[46] The rate of leakage in the national natural gas infrastructure has been widely studied. A recent widely-cited study by Alvarez et al. (2018) estimated a national average leakage rate of 2.3% of consumption across the entire national natural gas supply chain. CARB also maintains an inventory of greenhouse gas emissions in California which includes data about methane leakage, but since California imports approximately 90% of its natural gas it is more accurate to use a national average leak rate. The California Energy Commission recently estimated the behind-the-meter leakage rate for natural gas infrastructure in single family homes to be 0.5% (Fischer et al. 2018), which we add to the 2.3% figure to arrive at a total leakage rate of 2.8%.

Methane leakage is assumed to be reduced 40% by 2030, consistent with the California Air Resources Board Short-Lived Climate Pollutant Strategy and previously proposed EPA regulations on methane leakage from oil and gas wells under the Obama Administration[47]. California imports ~90% of its natural gas and most fugitive methane emissions happen during production, so federal regulations, or lack

[45] While we use the 100-yr GWP in this report in accordance with CARB and other GHG inventory protocols, we note that conventional GWP metrics cannot universally equate short-lived climate pollutants like methane with long-lived GHGs like CO_2. A shorter time horizon GWP may sometimes be appropriate when considering near-term and peak warming, but even the 100-yr GWP can underestimate the primacy of CO_2 for the long-term goal of climate stabilization (Allen et al. 2016)..

[46] The mass-based 100-year GWP of methane is 25 times higher than CO_2. This is based on the IPCC Fourth Assessment Report (Forster et al. 2007) and is used in the California GHG inventory, although more recent research is consistent with a somewhat higher GWP (see, e.g. Etminan et al. (2016). However, when calculating the GHG emissions from natural gas leakage, the molar-based GWP (not the more commonly reported mass-based metric), is the relevant GWP number, because this accounts for the difference in molar masses between CH_4 and CO_2. The molar-based GWP of methane is 9 times that of CO_2.

[47] The Obama administration previously set a goal to reduce methane emissions from the oil and gas sector to 40 to 45 percent below 2012 levels by 2025, and the EPA began instating regulations to help achieve this goal while President Obama was in office (see US EPA, 2016). Under the Trump administration, many of these regulations have been rolled back (see Tollefson, 2018).

thereof, are likely to have a big effect on fugitive methane emissions associated with natural gas use in California homes. Note that methane regulations on new oil and gas wells have been rolled back under the current administration, and no new regulations on existing wells are currently under consideration. If new federal methane regulations are not put in place by 2030, our assumption about a future 40% reduction in methane leakage may prove to be optimistic.

2.6.4 FUGITIVE EMISSIONS OF HIGH-GWP REFRIGERANT GASES

Leakage is also an issue with the refrigerants used in air conditioning units and heat pumps. The most commonly used refrigerants today still have an extremely high global warming potential. R410A, a common refrigerant currently used in new residential AC and heat pump systems including water heaters, has a 100-yr GWP of 2088. For heat pump clothes dryers, a common refrigerant is R134A (GWP 1430). In our 2020 estimates we assume that the current refrigerants listed above are used.

Efforts are currently being made in the refrigerant industry to identify lower-GWP refrigerants. The most promising replacement for R410A is R32 (GWP 675), and for R134A it is R1234yf (GWP 4)[48]. In our 2030 and 2050 estimates of refrigerant leakage, we assume that this next generation of refrigerants is used.[49] For heat pump water heaters, the technology exists to use CO_2 as a refrigerant (GWP 1), and this approach can be used for hydronic HVAC heat pump systems as well, but not currently for air-to-air systems. For smaller heat pump HVAC applications, hydrocarbon refrigerants such as propane (GWP 3) are also beginning to be used in certain applications. However, these refrigerants are flammable, so at least in the near term their use will be restricted to applications that require only small volumes of refrigerant.

[48] See California Air Resources Board (2017)

[49] CARB has proposed (but not yet enacted) bans on higher-GWP refrigerants in stationary AC units as part of its efforts to meet the state's goal of reducing HFC emissions to 40% below 2013 levels by 2030.

Note that the fugitive emissions of refrigerants are much higher (as a percentage of indirect electricity emissions) than what is reported in the CARB inventory, because the CARB inventory does not include the fugitive emissions of CFCs such as HCFC-22 (GWP 1810) which are being phased out under the Montreal Protocol. As residential customers replace their older HCFC-22 equipment with newer HVAC units (regardless of whether it is a standard AC system or an HVAC heat pump), the fugitive GHG emissions caused by leakage of their equipment will not increase significantly if both their old and new refrigerants have a similar GWP, but it will increase significantly as measured by the CARB inventory since the fugitive emissions from their new system will now be counted. To estimate refrigerant leakage by technology type, we referred to CARB estimates of typical leakage rates for each technology.[50] Details are in Appendix C: Additional Methods Detail.

2.7 Grid Impacts

Electric grid impacts of electrification are estimated using the hourly electricity demand profiles from the building simulation results. The average load is calculated, weighted by the assumed share of each building type by climate zone, and the assumed technology adoption rate.

Table 2-11 below illustrates this scenario of electric end use adoption in 2020, 2030 and 2050. This electrification adoption scenario represents one plausible “high electrification” future, in a world in which heat pump adoption is based largely on consumer economics with minimal other adoption barriers. This scenario, thus, is not a forecast, but is meant to test the potential of high building electrification on the bulk grid system.

[50] Data obtained through communications with CARB staff.

Table 2-11 Projected penetration of electric equipment in 2020, 2030 and 2050

	2020 Penetration (% of stock)	2030 Penetration (% of stock)	2050 Penetration (% of stock)
Share of all-electric low-rise residential homes	0%	26%	86%

Penetration represents the share of all-electric equipment among the entire stock of all fuel types.

This approach is intended to be a rough screen of future grid impacts to test whether building electrification is likely to exacerbate peak loads, or, conversely, improve the load factor of the system (the ratio of average to peak load). An improved load factor can lead to lower electricity rates over time through more efficient utilization of electric grid infrastructure.

3 Results

3.1 Greenhouse gas emissions

We estimated greenhouse gas (GHG) emissions associated with residential buildings from both fossil fuel combustion (indirectly from electricity use and directly from natural gas use) and fugitive emissions of methane and refrigerant gases. An all-electric single family home is estimated to reduce annual GHG emissions by 33 - 56% in 2020 and by 76 – 88% in 2050 compared to a natural gas-fueled home. The ranges reflect differences based on building vintages and climate zones. Smaller homes with smaller heating and cooling demands, including low-rise multifamily homes, save less GHG emissions per home on an absolute basis, but see a similar percentage reduction in GHG emissions by 2050 (Table 3-1).

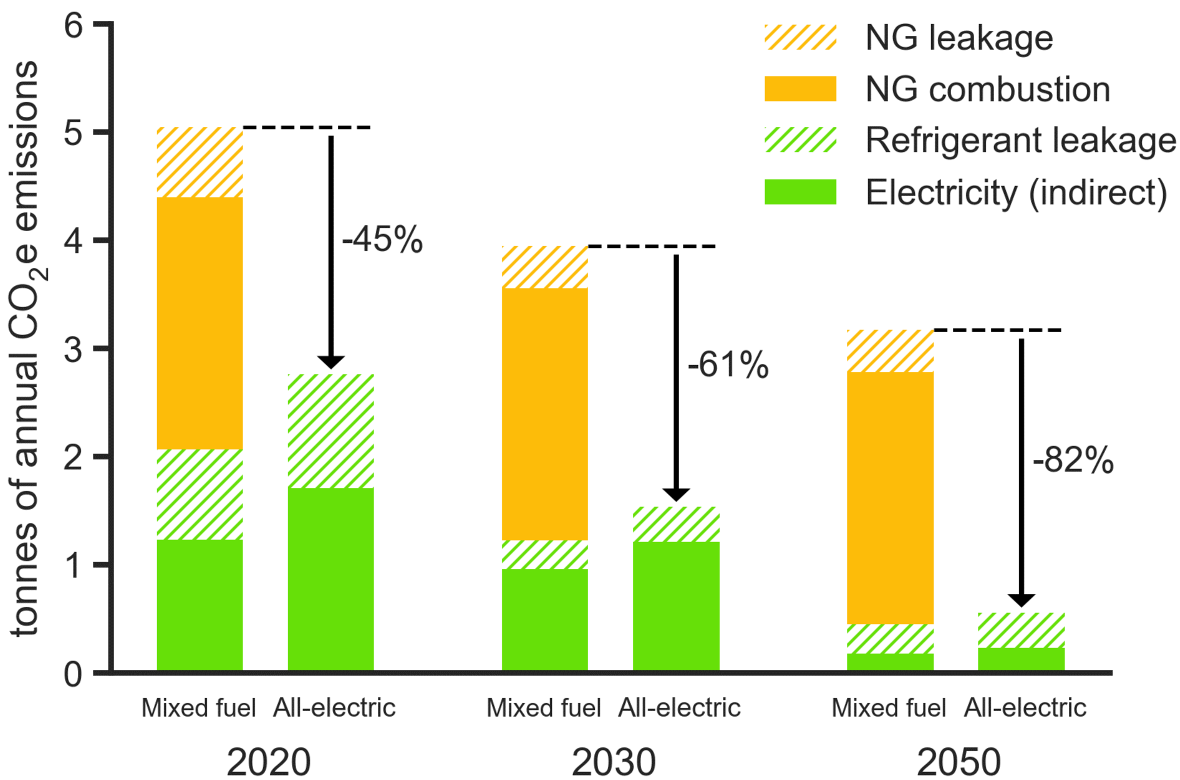
Table 3-1: Greenhouse gas savings achieved in an all-electric home relative to a natural gas-fueled home, tonnes of CO_2e annually saved, and percent reduction relative to gas

	2020	2030	2050
Single family	1.0-2.6 (33%-56%)	1.2-2.7 (52%-72%)	1.4-2.9 (76%-88%)
Low-rise multifamily	0.4-1.4 (25%-46%)	0.6-1.5 (49%-65%)	0.7-1.7 (74%-85%)

Percentages show the percent reduction of GHG emissions achieved in an all-electric home relative to a natural gas-fueled home. Ranges represent the spread across climate zones and across vintages. Homes without AC in the mixed fuel case (new construction in climate zone 3) are excluded.

Figure 3-1 illustrates this result for a 1990s vintage single family home in Sacramento. Here, emissions are reduced by 45% in 2020 and by 82% in 2050. The total magnitude of annual GHG emissions savings achieved by retrofitting to an all-electric home is about 2 tonnes of CO_2-equivalent in 2020, in this example, and closer to 3 tonnes in 2030.

Figure 3-1: Annual GHG emissions from a 1990s vintage single family home for Sacramento



Electricity emissions are based on the High Electrification scenario consistent with SB 100; see the greenhouse gas methodology section for more details. The 2030 and 2050 bars assume that the next generation of low-GWP refrigerants are used in all applicable heat pump systems modeled, including air conditioners, HVAC heat pumps, heat pump water heaters, and heat pump clothes dryers. We do not estimate refrigerant leakage from refrigerators and freezers, but these fugitive emissions would be the same in both electric and mixed fuel homes. We assume that by 2030, fugitive methane emissions are reduced by 40%, as mandated by the CARB Short-Lived Climate Pollutant Strategy and as previously set as a goal by the Obama administration. We based our calculations of fugitive refrigerant emissions on CARB data as described further in Appendix C.

The largest driver of greenhouse gas emissions savings in all-electric buildings comes from eliminating carbon dioxide emissions from natural gas combustion. In general, homes in Northern California, which require more energy for space heating and cooling, have a larger potential for emissions savings from all-electric homes than in Southern California.

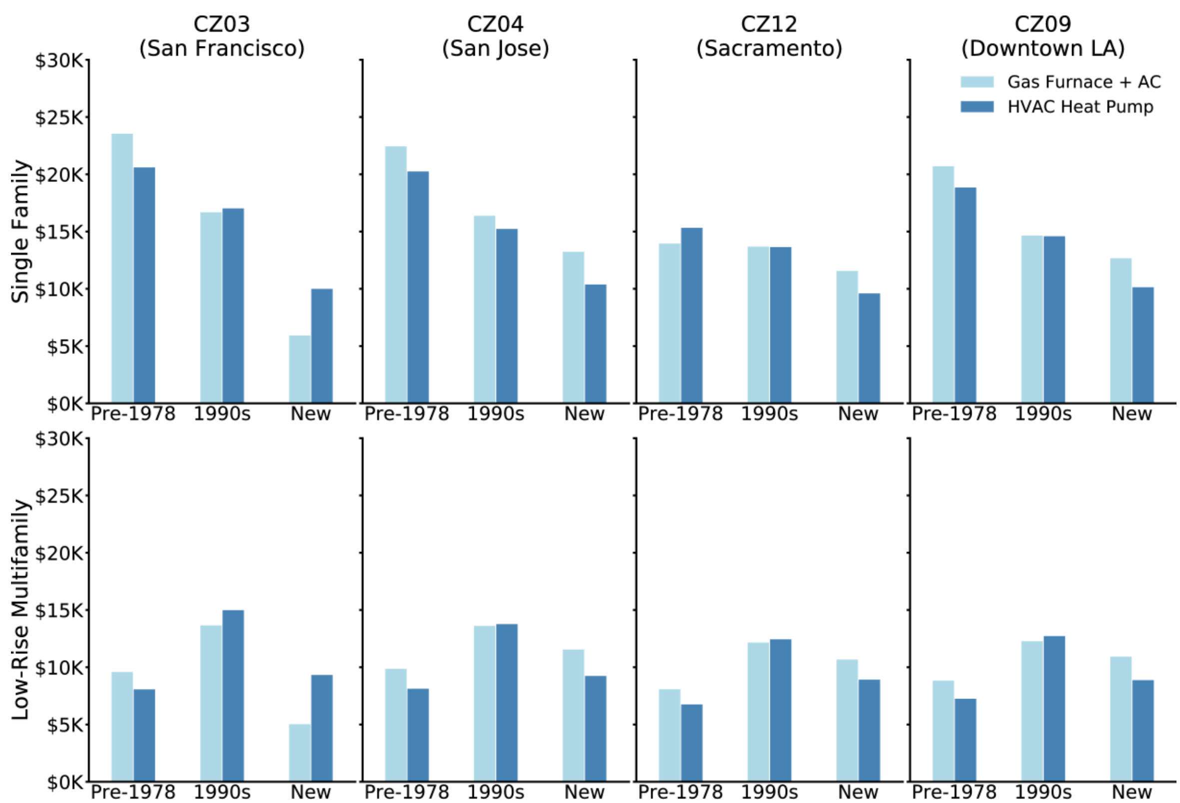
3.2 Capital Cost Comparisons

3.2.1 HEATING, VENTILATION AND AIR CONDITIONING SYSTEMS (HVAC)

Common high-efficiency equipment

Overall, we find capital cost savings from heat pump HVAC systems compared to combined gas furnace and air conditioning systems. HVAC heat pumps show a capital cost advantage of up to $3,000 over a combined gas furnace and air conditioning system in retrofit situations for most homes modeled, even after considering the delayed replacement cost of AC equipment (Figure 3-2).

Figure 3-2: Capital cost of an HVAC heat pump compared to a gas furnace plus air conditioner system.

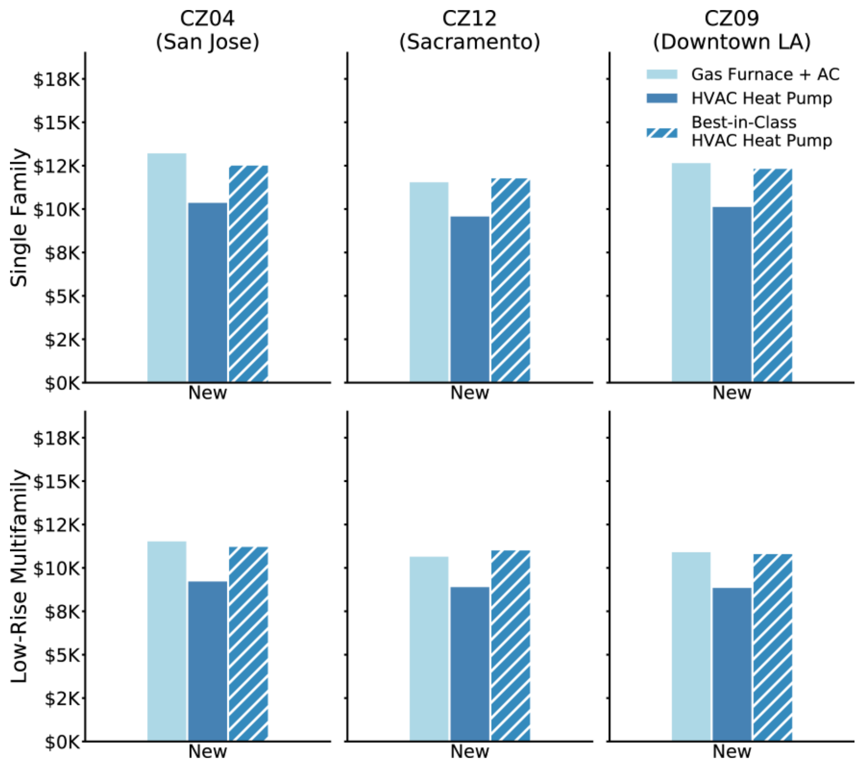


The additional electrical panel upgrade costs (adding a new 220V/30A circuit) for ducted split HVAC heat pumps diminish the cost advantage over the reference gas system in older retrofit homes using this technology. In comparison, mini-split ductless heat pumps and packaged terminal heat pumps (modeled for other retrofit homes) feature a significant cost advantage of $1,500-$3,000 due to the lower installation and modification costs compared to ducted heat pumps. Likewise, equipment cost savings make HVAC heat pumps more appealing in new construction homes, which avoid the demolition and modification costs associated with retrofits. However, for homes that do not have AC (modeled as new construction homes in San Francisco), an HVAC heat pump costs about twice as much as installing a gas furnace.

Best-in-class and emerging technology equipment

The additional cost of higher-performance heat pumps is assessed for new construction homes, to understand the impact of efficiency improvements and technology development. "Best-in-class products" are the highest-efficiency units that are available in the current market, featuring a 15%-40% improvement in efficiency compared to common high-efficiency products. The "emerging technology" products, which have a 40%-70% efficiency gain compared to the common high-efficiency products, were not included in the cost estimates.

Figure 3-3: Capital cost of HVAC heat pumps of two efficiency levels, compared to a combined gas furnace and air conditioner system, for new construction homes.

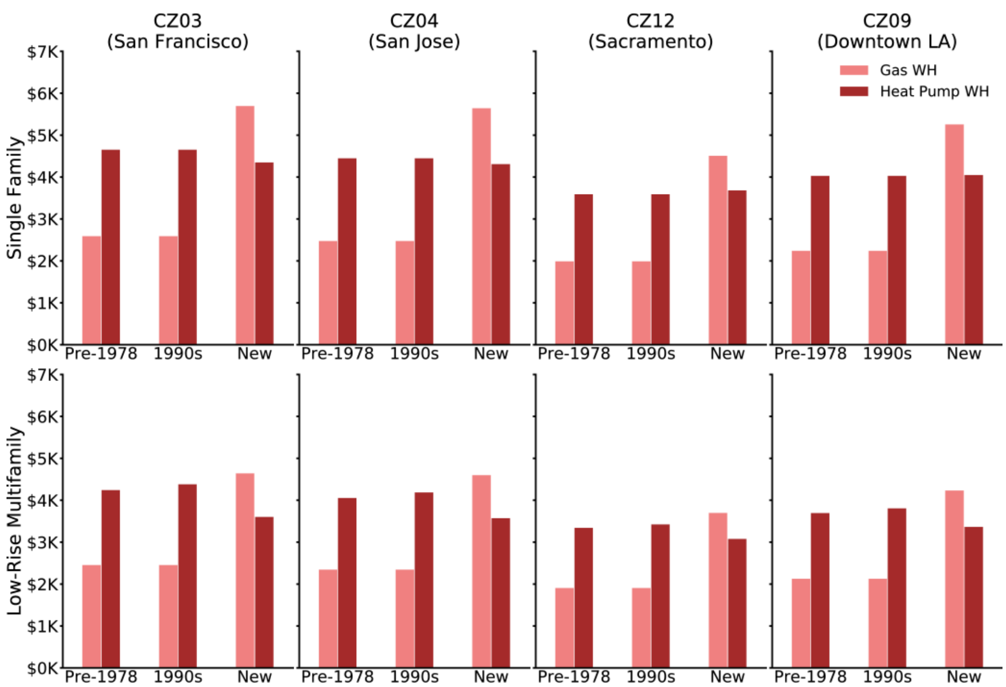


The cost premiums associated with the "Best-in-Class" HVAC heat pumps, as shown in Figure 3-3, almost erase the capital cost advantages of HVAC heat pumps over combined gas furnace and AC systems in new construction homes. The smaller best-in-class HVAC heat pump systems (modeled for San Jose, Coastal LA and Downtown LA) still maintain a slight cost advantage, whereas the higher-tonnage (more powerful) HVAC heat pumps are more costly and show a slight cost disadvantage over gas furnace plus AC systems.

3.2.2 DOMESTIC WATER HEATING

Heat pump water heaters (HPWHs) cost $1,000-$2,000 per household more than gas storage water heaters (modeled for all retrofit homes). However, HPWHs have a lower capital cost than gas tankless water heaters (modeled for new construction homes). The cost savings over gas tankless water heaters are driven by not having to run gas lines inside the home to connect the gas appliance.

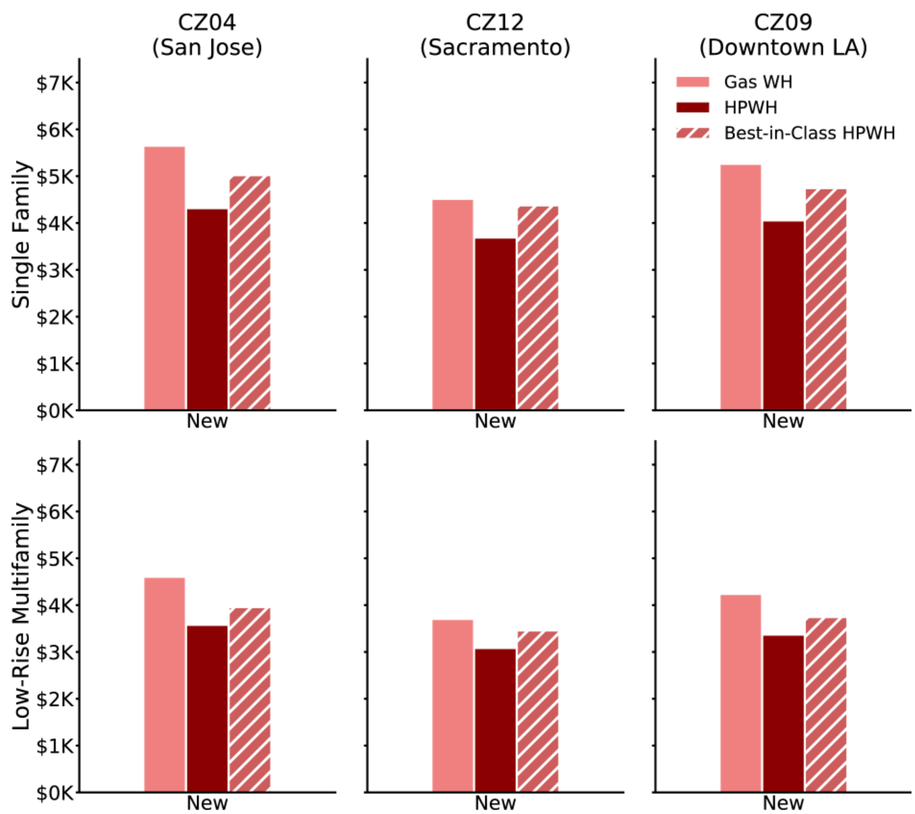
Figure 3-4 Capital cost of an electric heat pump water heater compared to a natural gas water heater.



Differences between climate zones are based primarily on differences in labor costs. Costs are presented on a per-unit basis.

Similar to HVAC systems, higher-performance HPWHs are investigated. The efficiency improvement of the best-in-class product is about 10% compared to the common high-efficiency product. The emerging technology product features a 30% efficiency gain over the common high-efficiency product. For most new construction homes, “Best-in-Class” HPWHs still deliver a capital cost advantage of ~$500 over gas tankless water heaters.

Figure 3-5: Capital costs of heat pump water heaters of two efficiency levels, and natural gas water heaters, for new construction homes



3.2.3 COOKING AND CLOTHES DRYING

Electric induction cookstoves and heat pump clothes dryers generally have slightly higher capital costs compared to gas stoves and gas clothes dryers. Electric resistance cookstoves and electric resistance clothes dryers are similar in capital cost to their gas counterparts (

Figure **3-6**).

Figure 3-6: Capital cost of cookstoves modeled. Figure on the left shows induction stoves (modeled for single family homes); figure on the right shows electric resistance stoves (modeled for low-rise multifamily homes)

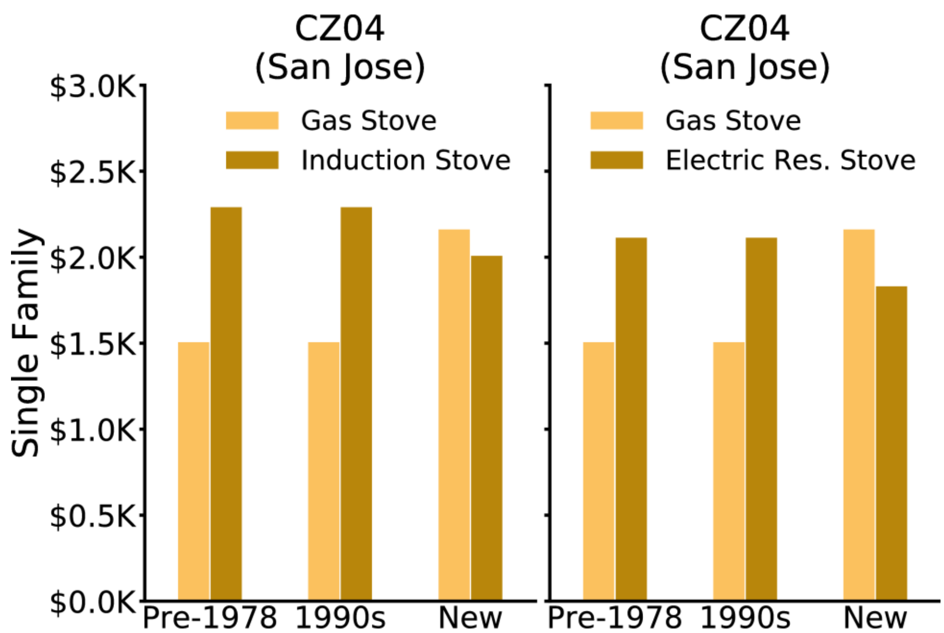
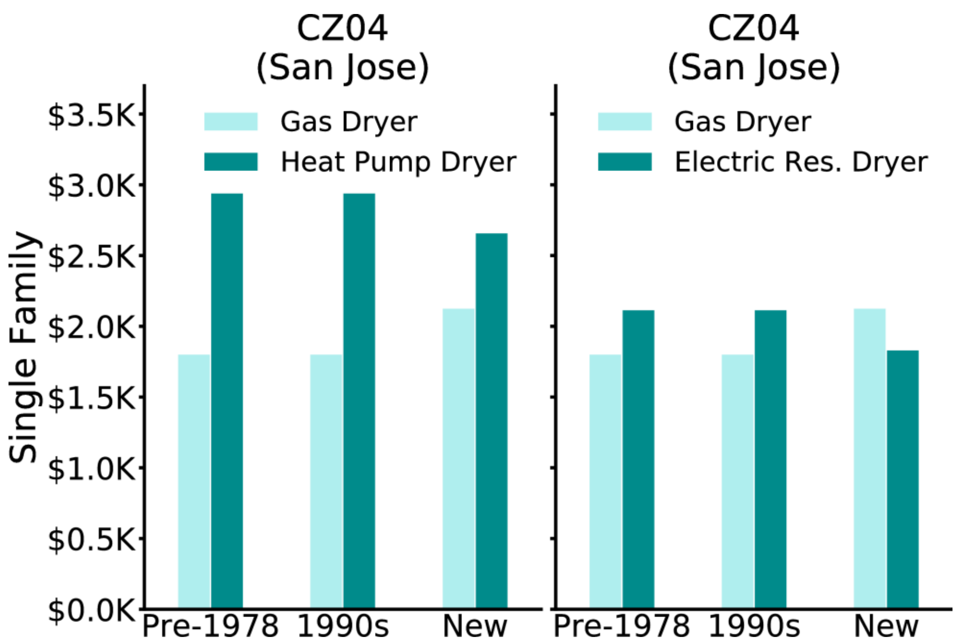


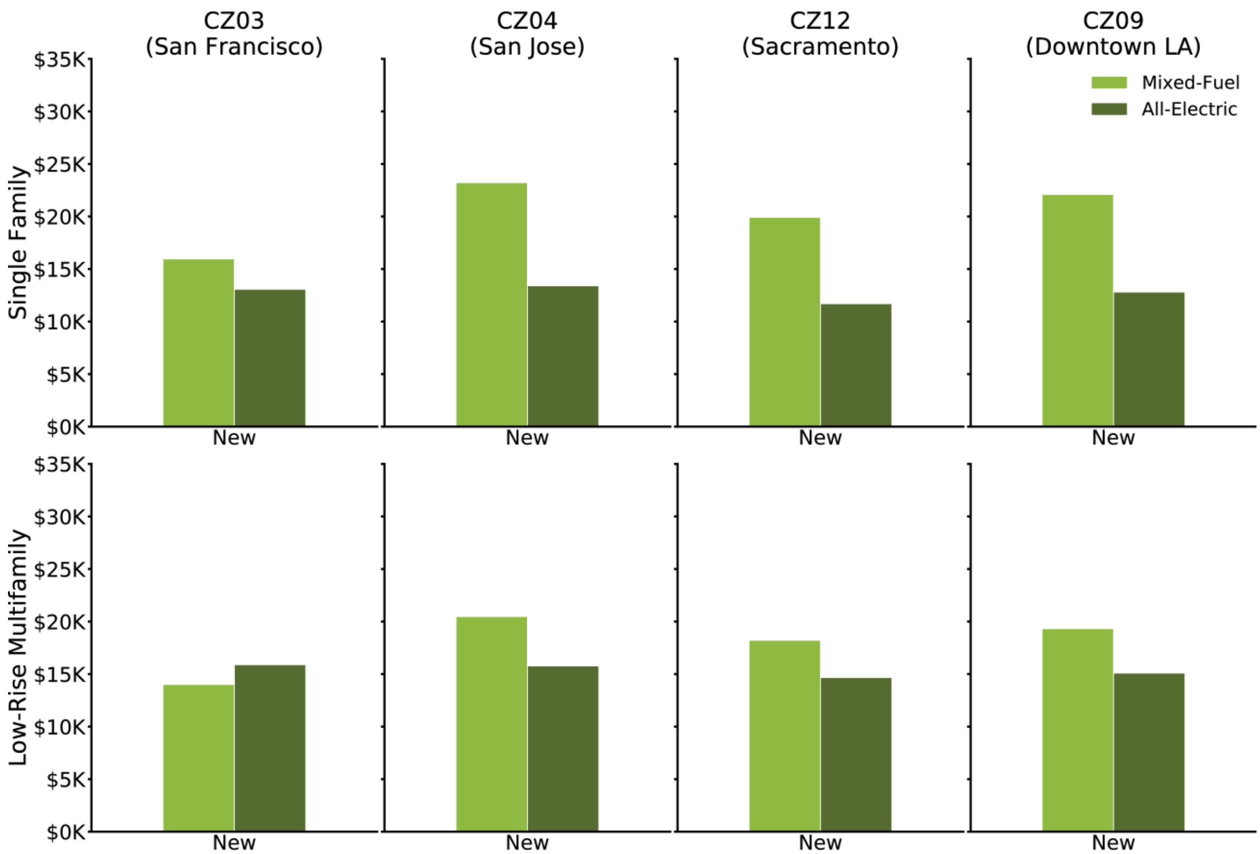
Figure 3-7: Capital cost of clothes dryers modeled. Figure on the left shows heat pump clothes dryers (modeled for single family homes); figure on the right shows electric resistance clothes dryers (modeled for low-rise multifamily homes)



3.2.4 ALL-ELECTRIC NEW CONSTRUCTION

All-electric new construction homes are likely to have a lower capital cost than their mixed-fuel counterparts. In addition to the lower capital cost of HVAC heat pumps compared to gas furnace plus AC systems, all-electric new construction homes avoid the gas infrastructure cost and gas interconnection cost needed for gas appliances. New construction homes also do not require electrical panel upgrades that can be required to retrofit existing homes to all-electric. By avoiding the aforementioned costs, an all-electric new construction home was estimated to have a capital cost advantage ranging from $3,000 to more than $10,000 over a mixed-fuel home, except for the low-rise multifamily home prototype in San Francisco (climate zone 3), where the mixed-fuel home was assumed to lack air conditioning.

Figure 3-8 Capital costs per unit of all appliances (HVAC, water heater, stove, and clothes dryer) and infrastructure (including gas connection costs) for new construction



3.3 Consumer bill impacts

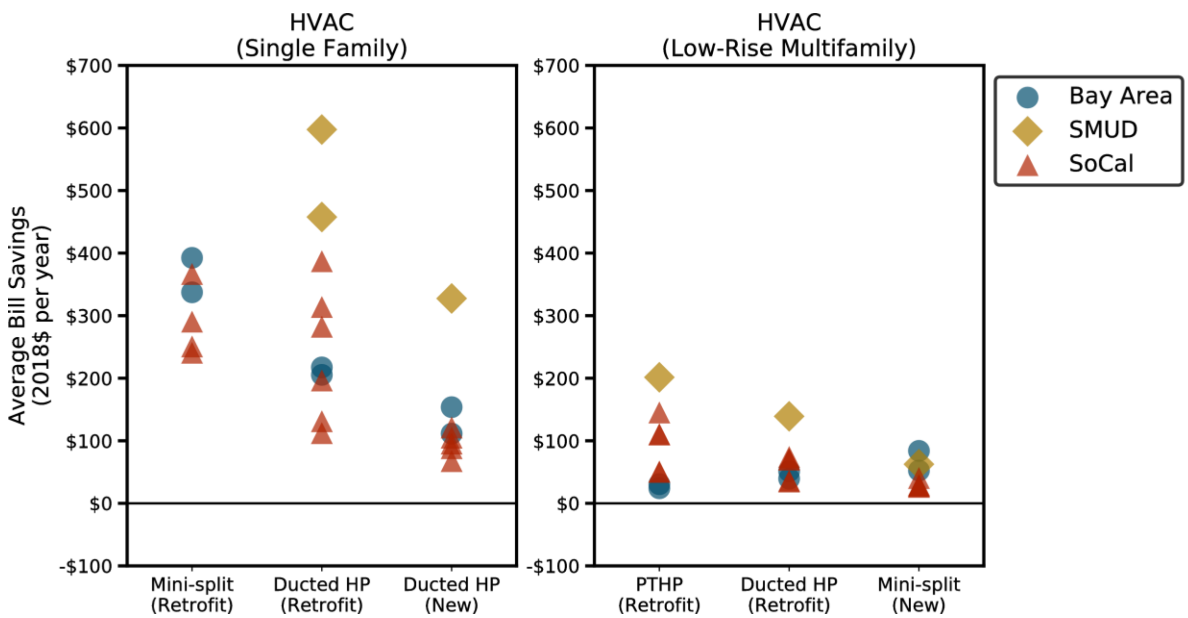
To quantify the consumer bill impacts of the electric building technologies investigated in this study, we report the average bill savings of an electric appliance over a gas counterpart. Average bill savings are presented as an annual value, amortized over the equipment lifetime. A discount rate is applied to account for the time-varying value of money.

3.3.1 HEATING, VENTILATION AND AIR CONDITIONING (HVAC) SYSTEMS

Common high-efficiency equipment

Our results indicate that HVAC heat pumps deliver bill savings for all homes for both retrofit and new construction (Figure 3-9), of up to $600 per year. The amount of bill savings is determined by the efficiency of the electric unit compared to the gas counterpart, the total energy consumption, and the electricity rates. The highly efficient heating cycle associated with HVAC heat pumps drives bills savings, as well as the higher efficiency of cooling compared to AC units in mixed-fuel homes. The larger single family homes and those of older vintages benefit more from switching to HVAC heat pumps due to higher heating and cooling demands. Electricity rates also drive differences: SMUD's low rates allow for much higher annual bill savings (up to $600/year) than other utility service territories (up to $400/year). Over the long term, bill savings for HVAC heat pumps could increase if gas retail rates increase faster than electric rates.

Figure 3-9 Average consumer bill savings from HVAC heat pump adoption

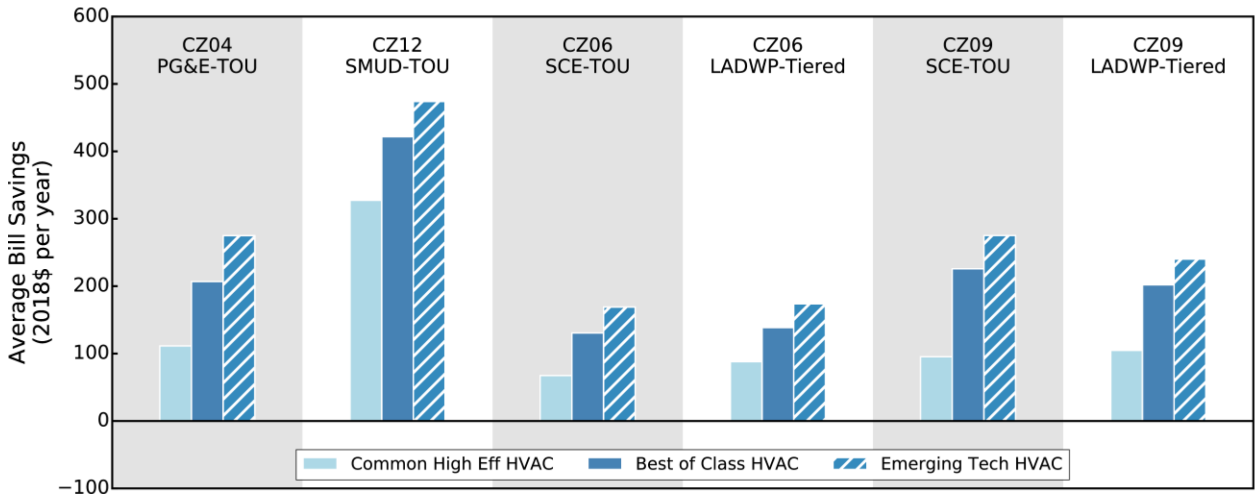


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal). Savings are relative to combined gas furnace and air-conditioner (AC) systems (except for new construction in San Francisco where AC is not considered). Positive values represent savings in combined annual electric and gas bills. Modeled technologies include mini-split heat pumps, ducted split heat pumps, packaged terminal heat pumps (PTHPs), and central heat pump water heaters and chillers combined with hydronic radiators (HPWH + Central Chiller).

Best-in-class and emerging technology equipment

Higher-performance HVAC heat pumps can generate significant additional bill savings for consumers, more than double the savings achieved by switching to the common high-efficiency product in most regions. The advantage in bill savings is greater in regions with higher electricity rates (SCE and PG&E).

Figure 3-10 Average consumer bill savings for higher-performance HVAC heat pumps



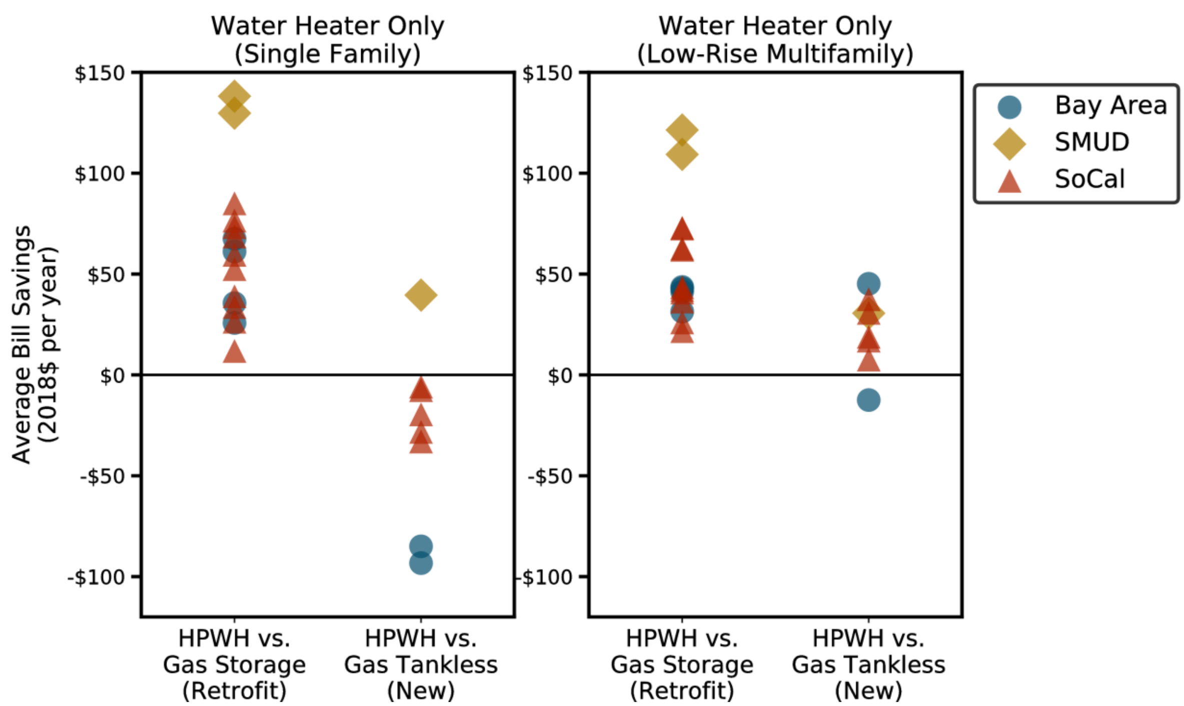
Annual bill savings shown for a new single family home, comparing a high-efficiency system (Common High-Eff HVAC), best-in-class system (Best-in-Class HVAC), and emerging technology system (Emerging-Tech HVAC). Each group represents one utility service territory in San Jose (CZ04), Sacramento (CZ12), coastal Los Angeles (CZ06) and downtown Los Angeles (CZ09).

3.3.2 WATER HEATING

Common high-efficiency equipment

Bill savings from switching to heat pump water heaters (HPWHs) do not show a clear trend across various technologies and home types. HPWHs deliver bill savings in all climate zones when compared to gas storage water heaters (modeled for retrofit homes, but not for new construction). Bill impacts are more mixed when HPWHs are compared to more efficient gas tankless water heaters for new construction homes. Electricity rates also play a role: in SMUD where electricity rates are lower, HPWHs show bill savings relative to both gas storage and gas tankless water heaters.

Figure 3-11 Average consumer bill savings from adopting heat pump water heaters (HPWHs)

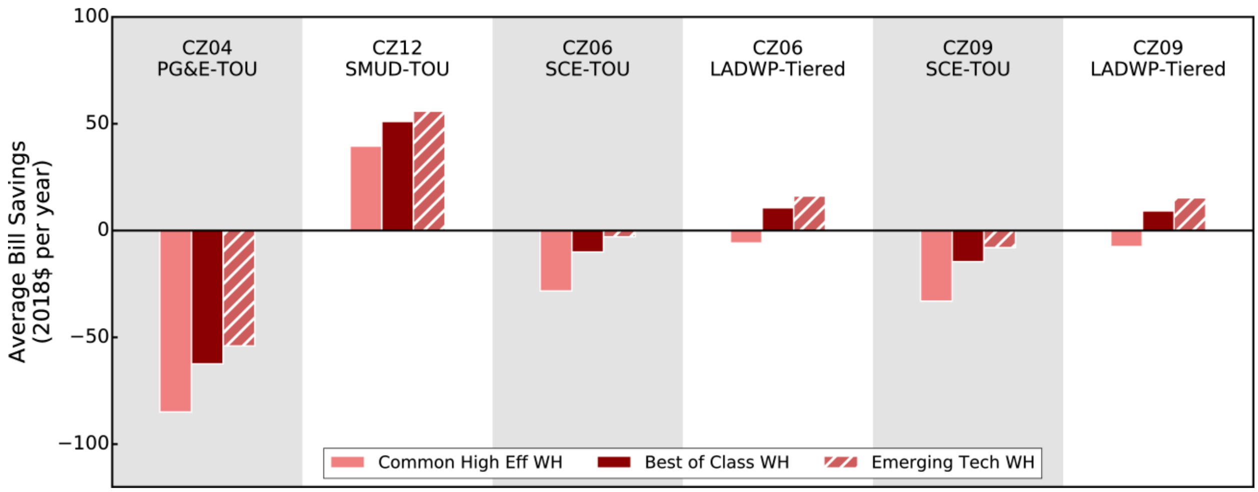


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal). Savings are relative to natural gas water heaters. Positive values represent savings in combined annual electric and gas bills.

Best-in-class and emerging technology equipment

Higher-performance HPWHs can slightly reduce consumer bills by $10-$30 per year. The efficiency improvements can lead to bill savings or bring consumers close to bill parity in most areas modeled (Figure 3-12).

Figure 3-12 Average consumer bill savings from switching to higher-performance HPWHs



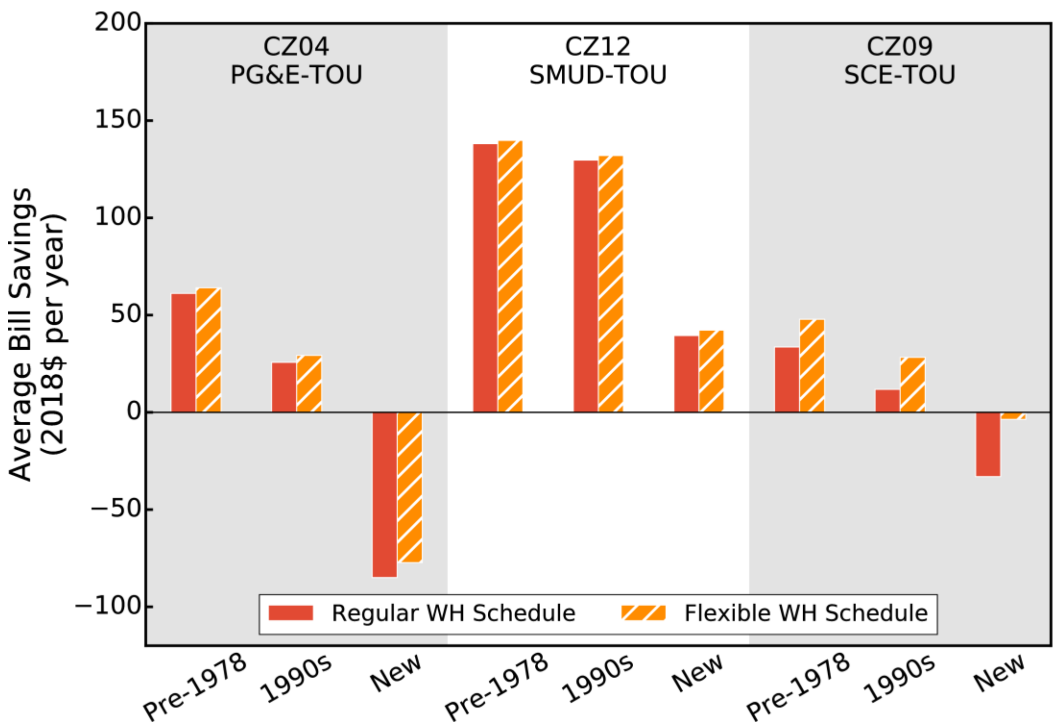
Savings are relative to a gas tankless water heater in a new construction single family home.

Flexible water heating sensitivity

We assess the impact of a flexible water heating schedule on consumer bills. We assume that the water heater runs at minimal power during the peak TOU hours and shifts the water heating to off-peak TOU hours. (We assume pre-heating; however, this is an arbitrary choice, as TOU rates are generally symmetric before and after the peak TOU period.) Energy consumption of HPWHs is higher in winter than in summer, especially during peak hours (Figure 3-14). The TOU rates investigated in this study capture the evening water heating peak demand but miss the morning water heating peak period.

Given existing rate structures, the customer benefits of flexible water heating are relatively limited. The customer benefits are highest under the SCE TOU-4-9 rate structure (Downtown Los Angeles) because of the relatively large TOU differentiation of $0.12 per kWh in winter (Figure 3-13).

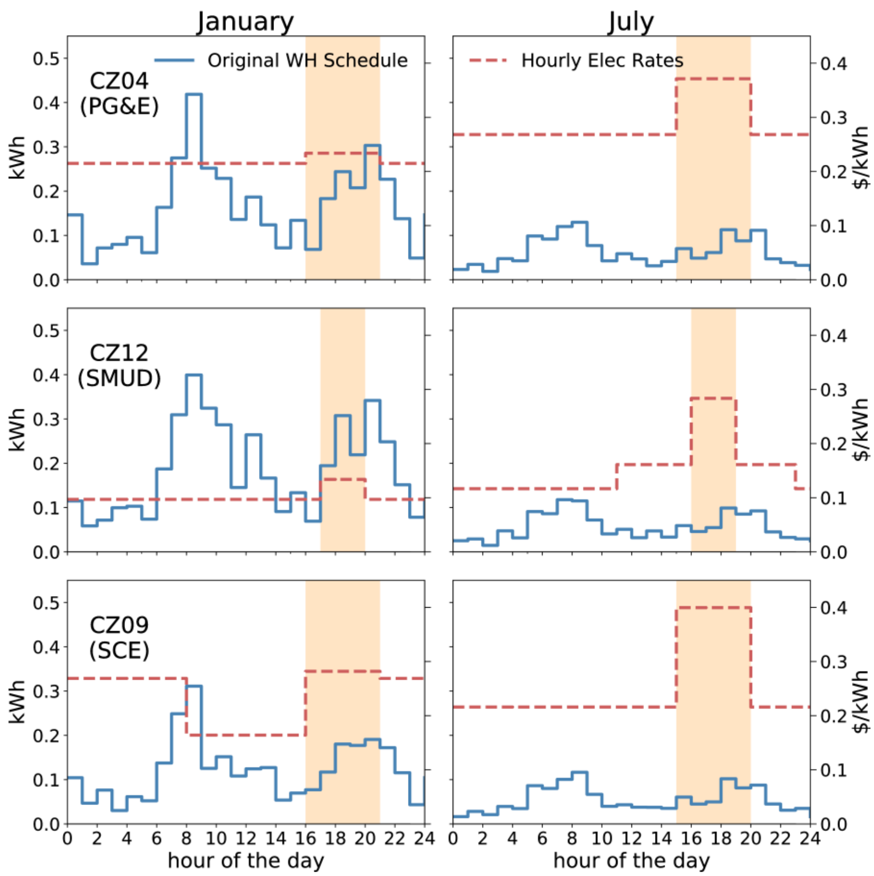
Figure 3-13 Average consumer bill savings from a flexible water heater schedule compared to a regular water heater schedule



Savings are relative to a gas tankless water in CZ04 (San Jose), CZ12 (Sacramento) and CZ09 (Downtown Los Angeles) for single family homes. The flexible schedule assumes that the water heater runs at minimal power during the peak hours and shifts the heating to hours before the highest priced TOU period.

Avoiding peak rates through flexible water heating schedules generates little bill savings under PG&E and SMUD TOU rates, because these rates feature a very small difference, less than $0.04 per kWh, between on-peak and off-peak (Figure 2-11). In the future, new rate designs that encourage the use of flexible water heating would have larger differences in TOU periods, particularly in winter when water heating demands are higher. This could help encourage the use of flexible, smart water heater technology.

Figure 3-14: Heat pump water heater energy consumption, and corresponding electric rates, for three climate zones

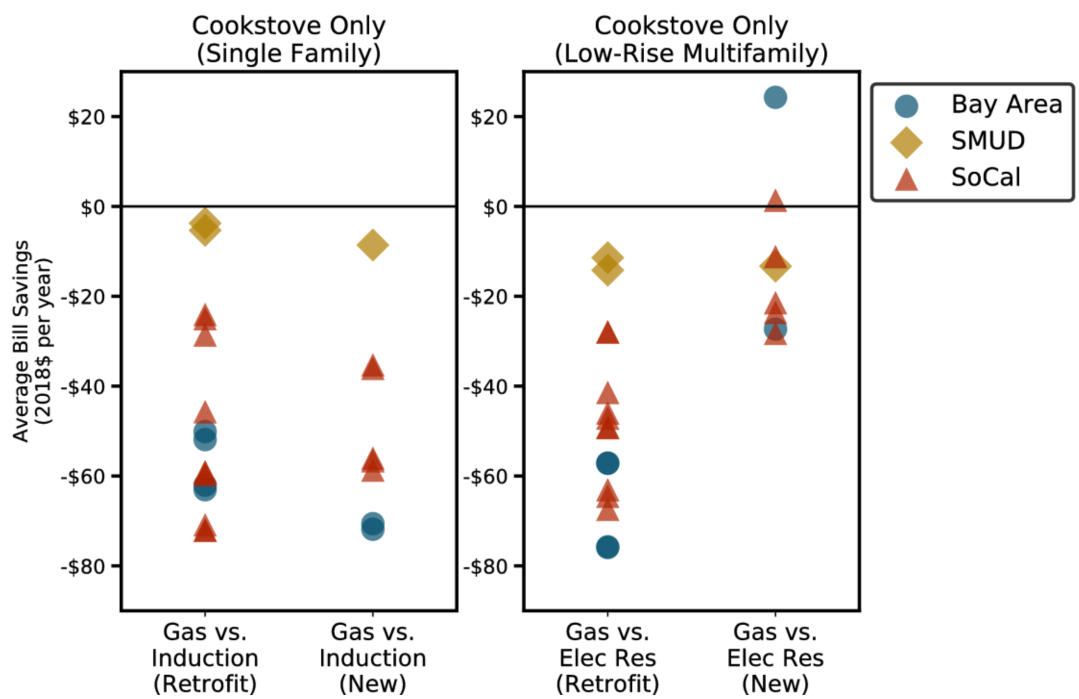


Red lines represent electricity rates. Blue lines show the water heating schedules modeled for new construction single family homes in CZ04 (San Jose), CZ12 (Sacramento) and CZ09 (downtown Los Angeles). The shade highlights the peak period under the TOU rate schedule modeled for PG&E, SMUD and SCE.

3.3.3 COOKING

Electric cookstoves, both induction and electric resistance, increase consumer bills relative to gas stoves, but the impacts are relatively low, at less than $80/year in the highest cases. Moderate differences in bill impacts appear across utilities, climate zones, and home types due to differences in total consumption under tiered gas rates (and tiered electricity rates, for LADWP).

Figure 3-15 Average consumer bill savings from adopting electric cookstoves

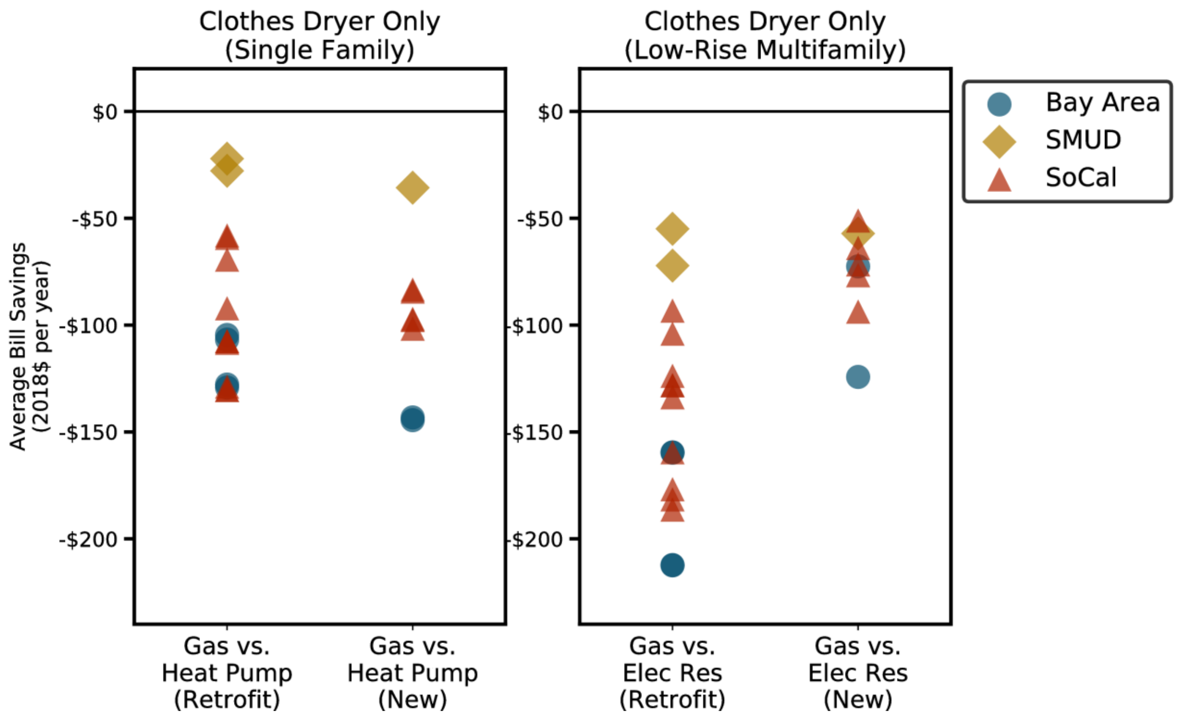


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal).

3.3.4 CLOTHES DRYING

An electric clothes dryer, using either heat pump or electric resistance technology, increases consumer bills relative to a gas counterpart. Bill increases range from $20/year to $220/year, depending on the utility rates, rate structures, and the type of home.

Figure 3-16 Average consumer bill savings from adopting electric clothes dryers

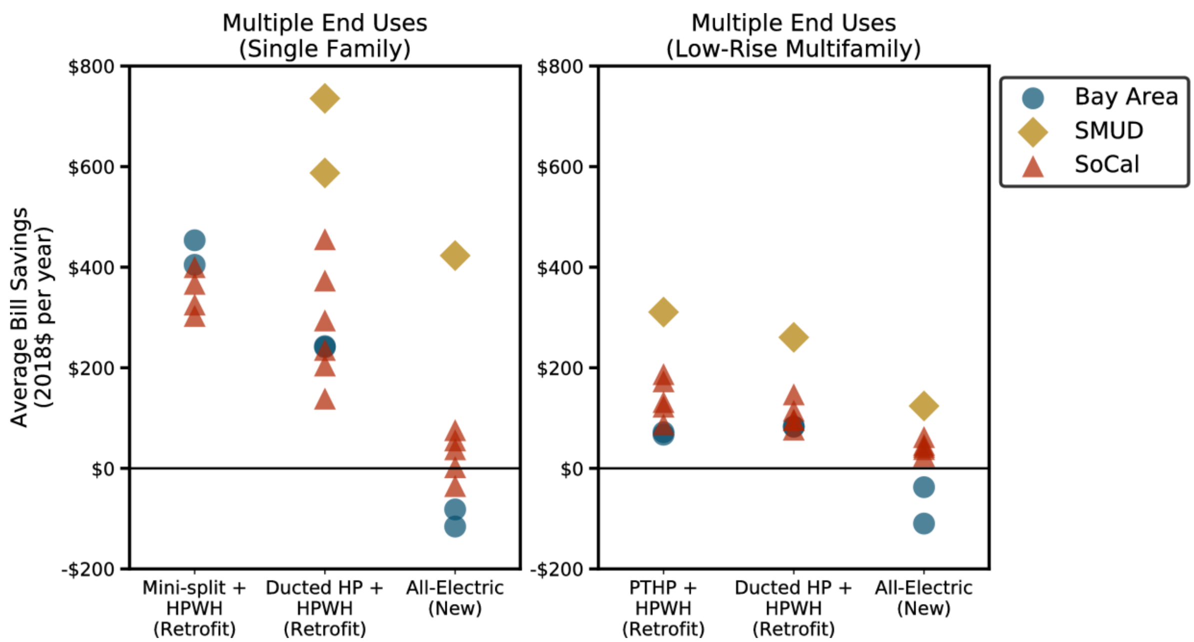


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal).

3.3.5 MULTI-APPLIANCE RETROFITS AND ALL-ELECTRIC NEW CONSTRUCTION

Electrifying both HVAC and water heating systems generates bill savings for all retrofit homes studied. The bill savings can be up to $750 per year in single family homes and up to $300 per year in low-rise multifamily homes (Figure 3-17). All-electric new construction homes also generate bill savings in many regions. Note that for this multi-appliance bill impacts analysis, we assume that only HVAC and water heating are electrified in retrofit homes, while in new construction homes, all appliances are electrified including cookstoves and clothes dryers.

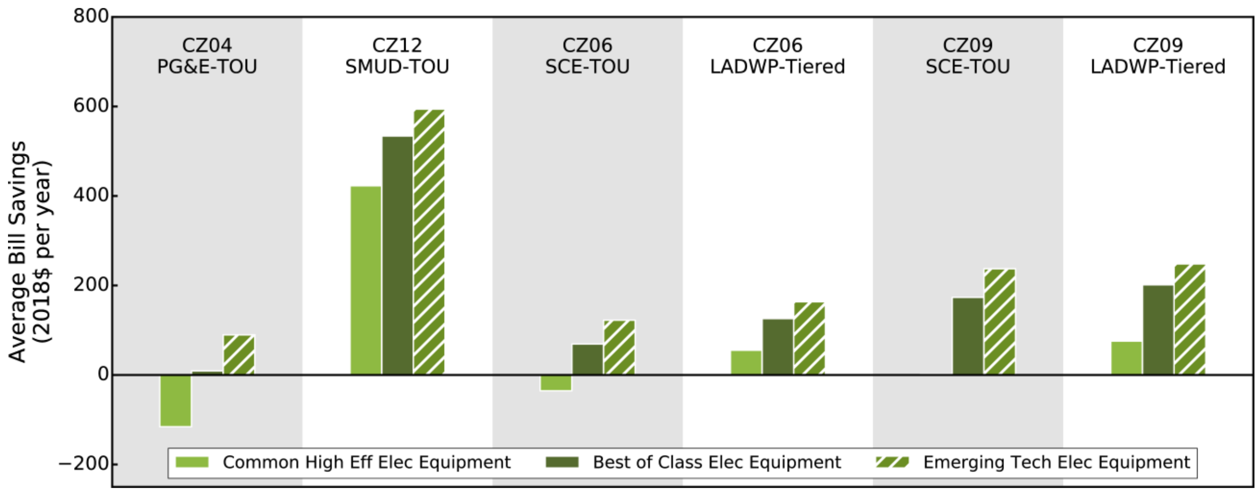
Figure 3-17 Average consumer bill impacts of electrifying multiple end uses, using base case assumptions



The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal). Savings are relative to gas end uses. For retrofit homes, bill impacts reflect electrifying both HVAC and water heating systems. For new construction homes, bill impacts of electrifying an entire home are shown including electric air source heat pump, heat pump water heater, cookstove and clothes dryer.

Switching from common high-efficiency products to best-in-class or emerging-technology products would reduce average bills by $100-$200 per year, generating bill savings for new homes in all climate zones studied (Figure 3-18).

Figure 3-18 Average bill savings from switching to multiple higher-performance electric end uses

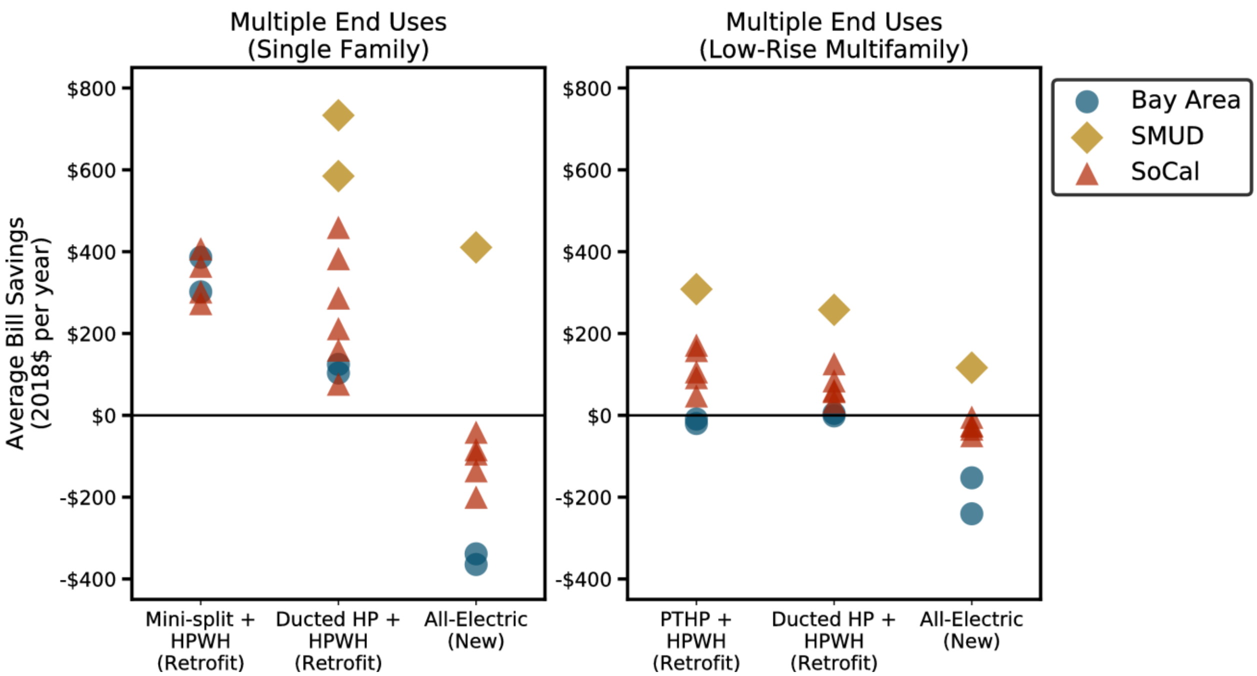


Savings are relative to gas end uses. The results are shown for a new single family all-electric home, comparing common high-efficiency, best-in-class, and emerging-technology HVAC heat pumps and heat pump water heaters. Cookstoves and clothes dryers in all three cases have the same efficiencies. Each group represents one utility service territory in San Jose (CZ04), Sacramento (CZ12), coastal Los Angeles (CZ06) and downtown Los Angeles (CZ09).

We also evaluated the impact on average consumer bills of an electric rate sensitivity, assuming that electricity and natural gas rates increase at the same annual percentage growth rate between 2019 and 2050. Electric rates for PG&E, SCE, and LADWP are assumed to increase at the same annual rate of change as SoCalGas's gas rates (including a cumulative 32% increase above inflation from 2018 through 2022), and electric rates for SMUD are assumed to increase at the same annual rate of change as PG&E's gas rates (including a cumulative 6% increase above inflation from 2018 through 2022). In this sensitivity, PG&E's electric rates are assumed to increase faster than the natural gas rates due to wildfire risk and liability, while SCE's, SMUD and LADWP's rates are assumed to increase at the same pace at the gas utility in their service territory. As a result, the largest difference in results between the base case assumptions and this rate sensitivity are seen in the "Bay Area" climate zones, representing PG&E's service territory.

The results of this sensitivity analysis reduce the average bill savings over the lifetime of the equipment or building relative to the base case assumptions (Figure 3-19).

Figure 3-19. Average consumer bill impacts of electrifying multiple end uses, electric rate sensitivity

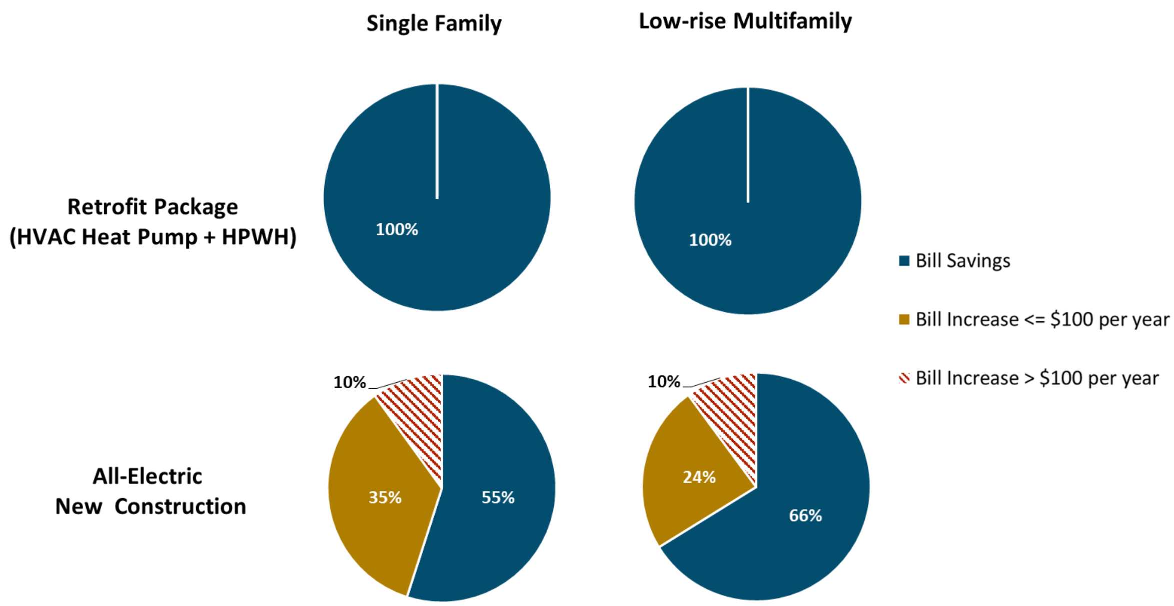


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal). Savings are relative to gas end uses. For retrofit homes, bill impacts reflect electrifying both HVAC and water heating systems. For new construction homes, bill impacts of electrifying an entire home are shown including electric air source heat pump, heat pump water heater, cookstove and clothes dryer.

3.3.6 SUMMARY OF AVERAGE BILL IMPACTS

The pie charts below summarize the share of homes in the study area that would see bill savings, bill increases of less than $100/year, and bill increases of more than $100/year.

Figure 3-20 Share of simulated households with bill savings from adopting electric end uses; results are weighted by the estimated share of households in each climate zone and utility service territory



The building simulation results are weighted using the share of households in each combination of climate zone and utility, as described in section 2.2.1. to create this summary figure. Average bill costs of HVAC heat pumps are compared against a combined gas furnace and air conditioner (AC) system except for a new construction home in San Francisco (Climate Zone 3) where we assume all homes do not have AC. For retrofit homes, we show the average bill impact of electrifying HVAC and water heating systems at the same time. For new construction, we look at an all-electric home with all four appliances modeled electrified.

3.4 Lifecycle costs and savings

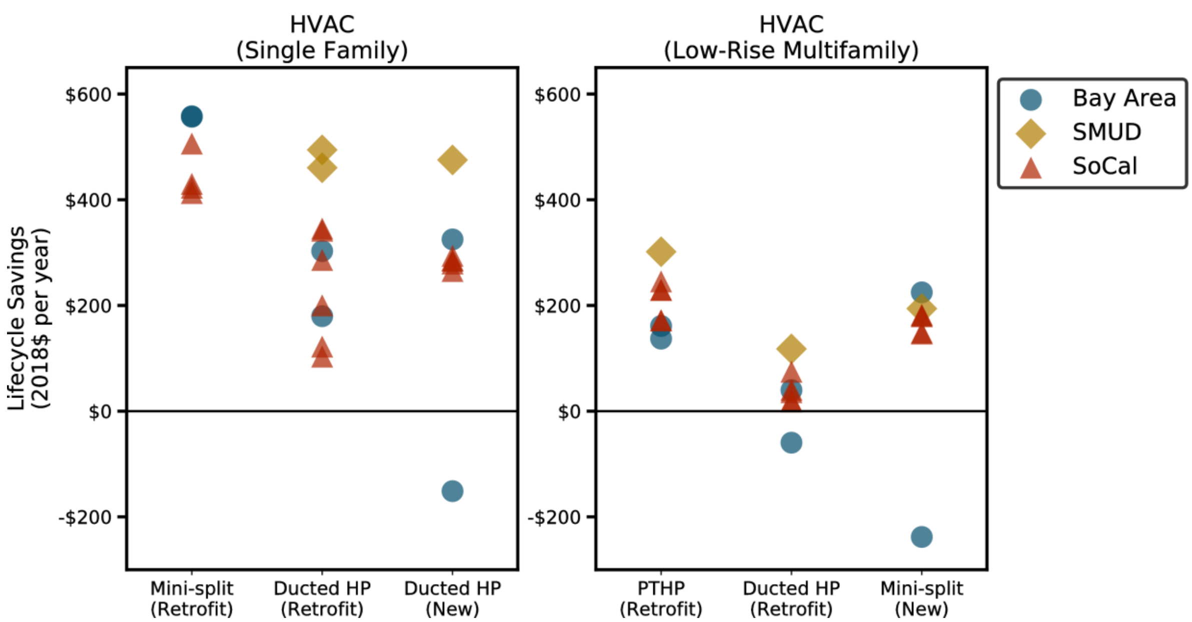
The lifecycle cost of an appliance represents the total cost of ownership, combining capital cost and bill costs. Lifecycle costs are presented in this study as an annual value, amortized over the equipment lifetime. A discount rate is used to account for the time-varying value of money. In this section, we evaluate the lifecycle costs and savings of the building technologies investigated in this study.

3.4.1 HEATING, VENTILATION AND AIR CONDITIONING (HVAC) SYSTEMS

Common high-efficiency equipment

The installation of HVAC heat pumps can result in up to $550 per year in lifecycle savings relative to a combined gas furnace plus air conditioner (AC) system (Figure 3-21). However, homes without AC incur an extra lifecycle cost of $200 per year by switching to an HVAC heat pump.

Figure 3-21 Lifecycle savings from adopting HVAC heat pumps

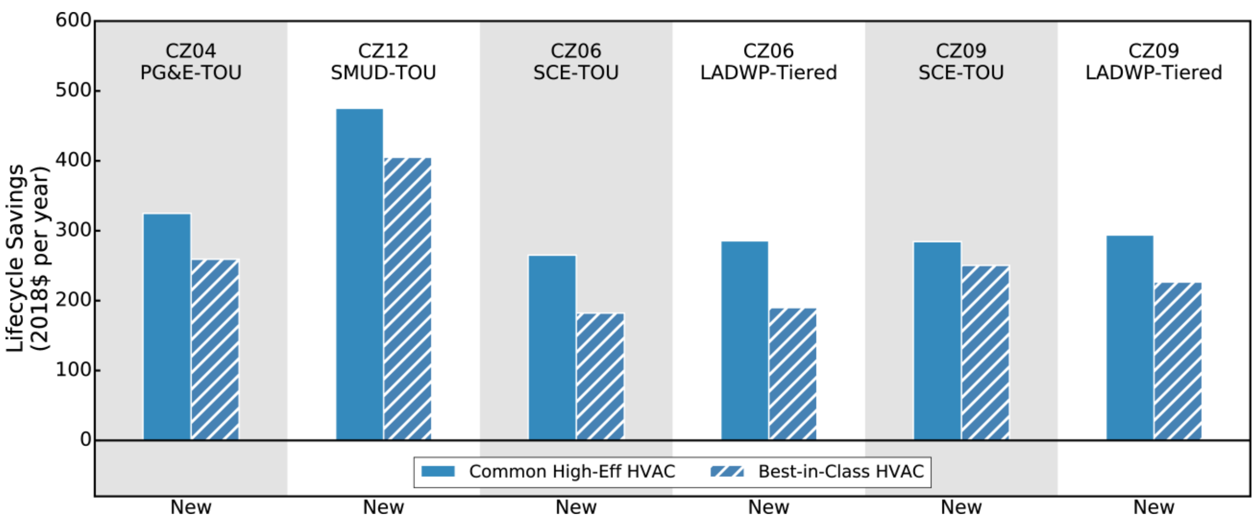


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal). Savings are relative to a combined gas furnace and air-conditioner (AC) system (except for the new home in San Francisco where AC is not considered). Positive values represent savings in both capital and operating costs throughout the lifetime of HVAC heat pump over the gas alternative system; negative values indicate costs. Modeled technologies include mini-split heat pump (Mini-split), ducted split heat pump (Ducted HP), and packaged terminal heat pump (PTHP).

Best-in-class and emerging technology equipment

Higher-performance heat pump systems in new construction applications deliver bill savings of up to $400 per year compared to a combined gas furnace and air conditioner (AC) system. Compared to common high-efficiency systems, higher-performance products would have higher lifecycle costs due to the increased capital costs. However, capital cost savings would still be positive relative to a combined gas furnace and air conditioner, so this might be a good target for incentives or codes to make sure consumers see both capital cost savings and bill savings, and to encourage market transformation so the costs of higher-performance units come down over time.

Figure 3-22 Lifecycle savings of higher-performance HVAC heat pumps



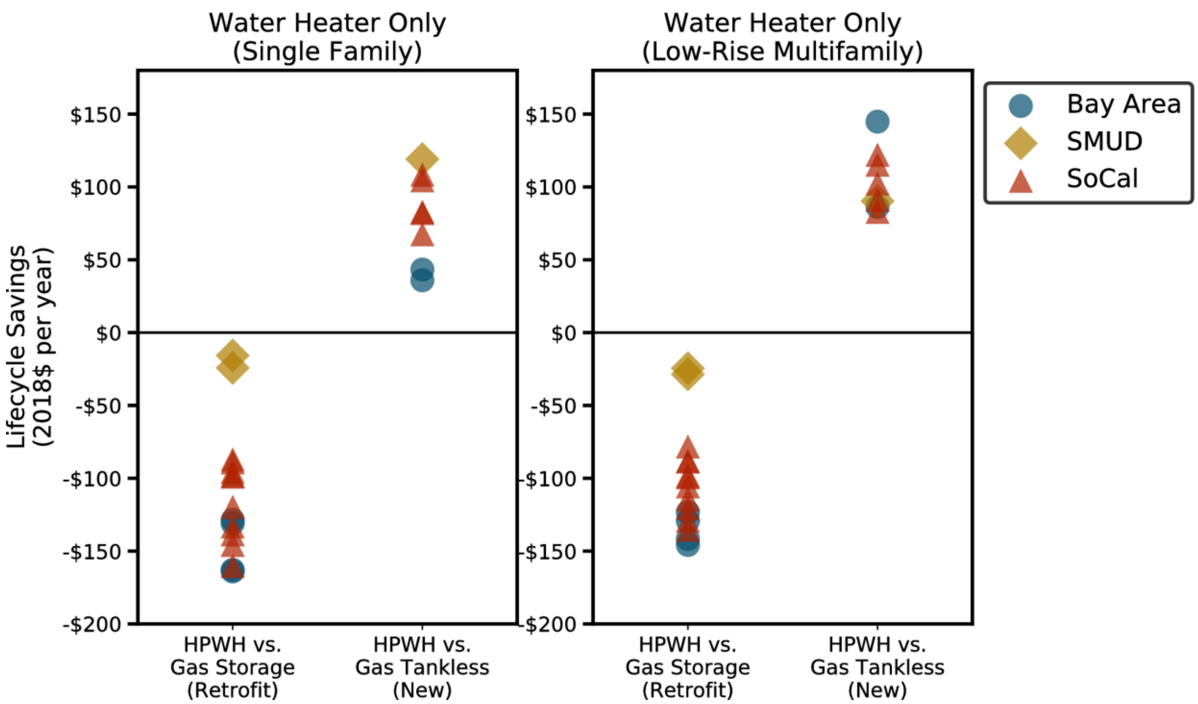
Savings are relative to a combined gas furnace plus air conditioner system.

3.4.2 DOMESTIC HOT WATER (DHW)

Common high-efficiency equipment

Heat pump water heaters (HPWHs) generate lifecycle savings of up to $150 per year over gas tankless water heaters in almost all home applications, but in retrofit homes, gas storage water heaters still appear to be the cheapest option (Figure 3-23). The net lifecycle costs of HPWHs are driven mainly by the capital cost.

Figure 3-23 Lifecycle savings from adopting HPWHs

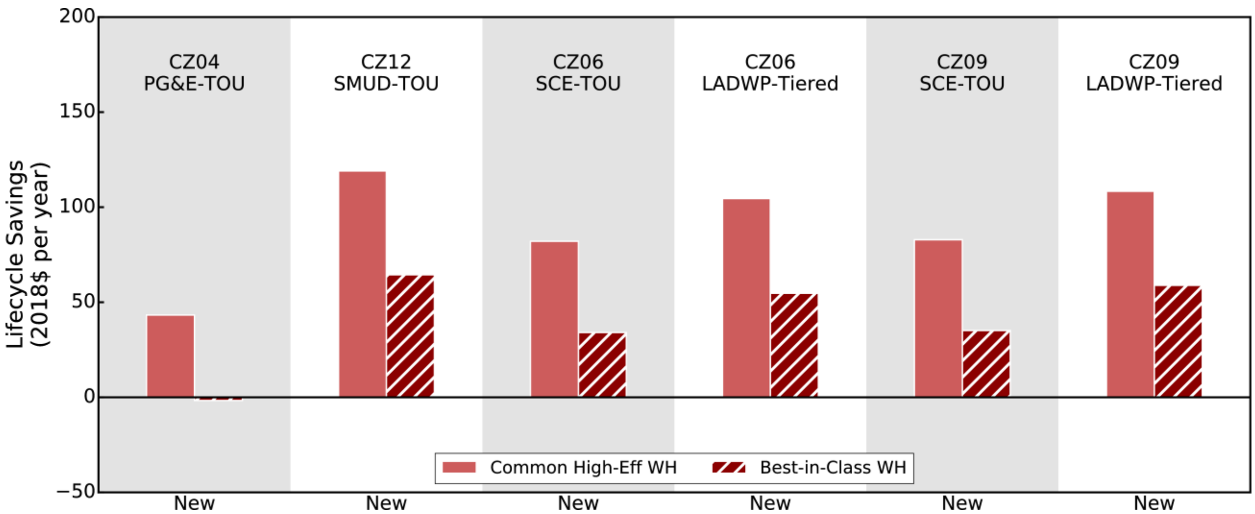


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal). Savings are relative to gas fired water heaters. Positive values represent savings in both capital and operating costs throughout the lifetime of an HPWH over the gas water heater; negative values indicate lifecycle costs.

Best-in-class and emerging technology equipment

Higher-performance "best-in-class" HPWHs show lifecycle savings over gas tankless water heaters in most new home applications. However, similar to HVAC heat pumps, higher-performance HPWHs deliver lower lifecycle savings compared to the common high-efficiency product. The small improvement in operating costs is not enough to compensate for the capital cost premiums of the higher-performance units.

Figure 3-24 Lifecycle savings of common high-efficiency and best-in-class HPWHs

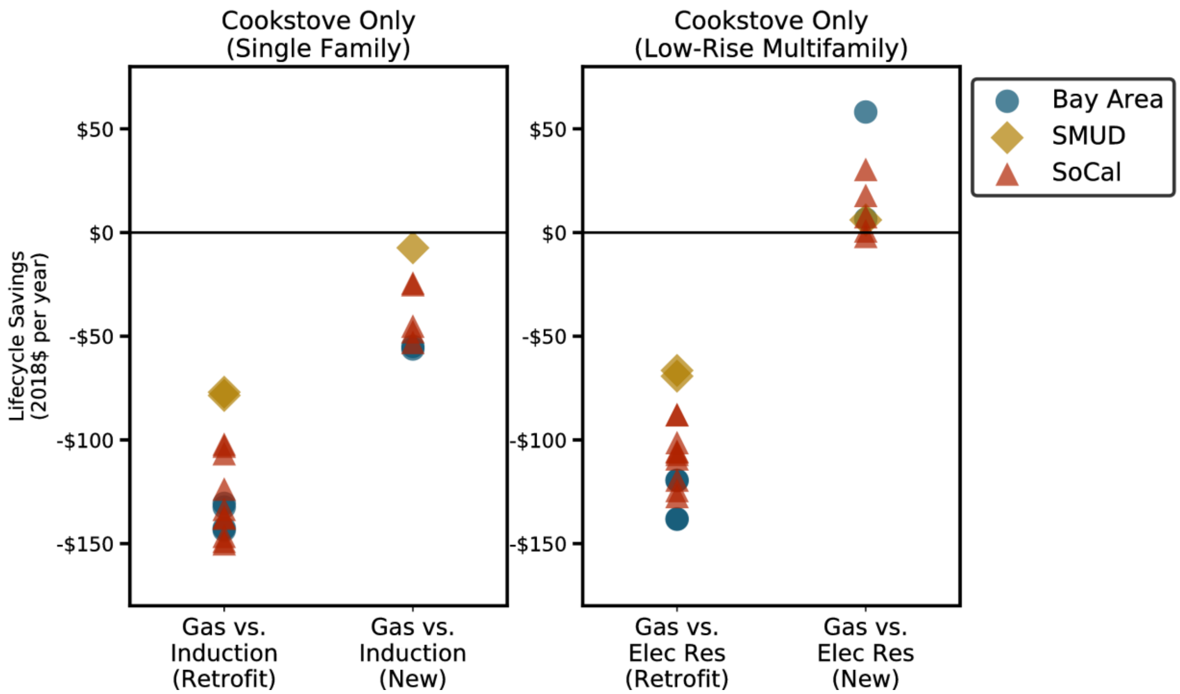


Savings are relative to a combined gas furnace plus air conditioner system. Savings are 0 for the best-in-class water heater in climate zone 4. Each climate zone compares two type of heat pump technology: a best-of-class HPWH (Best of Class WH) vs. a common high-efficiency HPWH (Common High Eff WH).

3.4.3 COOKING

Electrifying cooking generally incurs extra lifecycle costs, of up to $150 per year, for all types of homes. Induction cookstoves have higher capital costs than both gas stoves and electric resistance stoves in the current market. Nevertheless, installing electric cookstoves in new construction homes can avoid the cost of connecting gas lines to the kitchen, which makes electric resistance stoves a lower-cost option than gas stoves in new construction.

Figure 3-25 Lifecycle savings of electrifying cooking

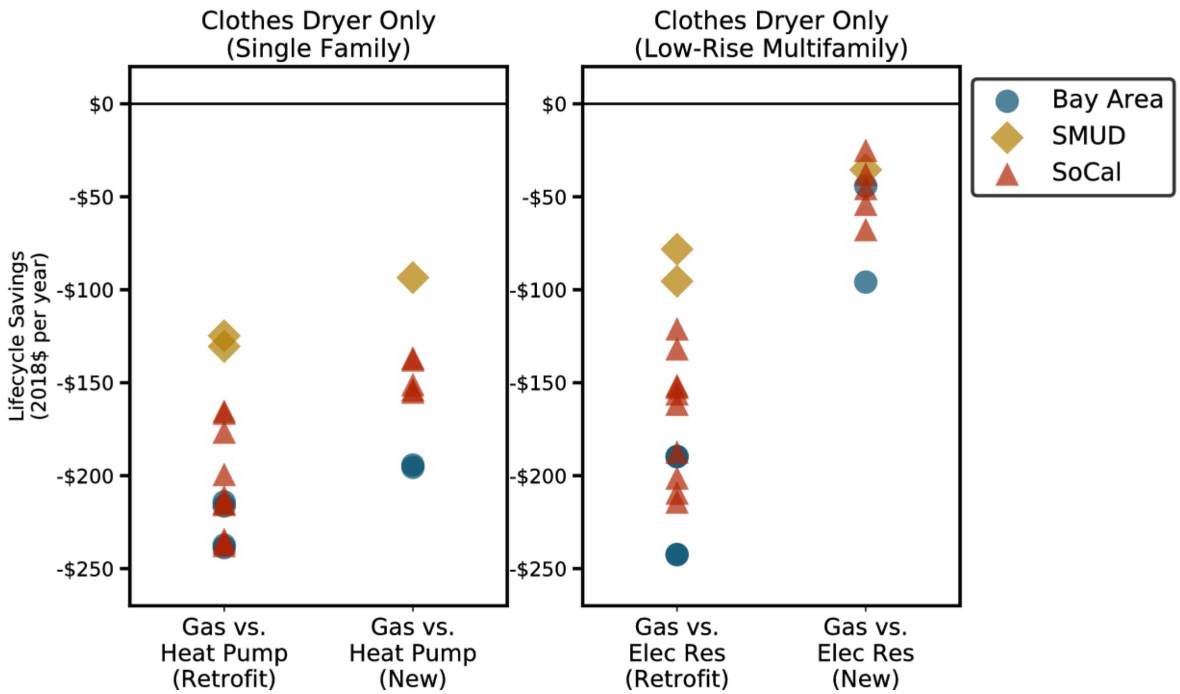


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal).

3.4.4 CLOTHES DRYING

Electric clothes dryers are more expensive than gas dryers, costing consumers up to $240 more per year in lifecycle costs. A heat pump clothes dryer is the most expensive option on a lifecycle basis, due to the higher capital costs. While an electric resistance clothes dryer is cheaper to install in new homes due to the avoided gas connection costs, the extra operating costs of up to $220 per year in electric bills make it less economic than the gas dryer on a lifecycle basis.

Figure 3-26 Lifecycle savings of electrifying clothes drying



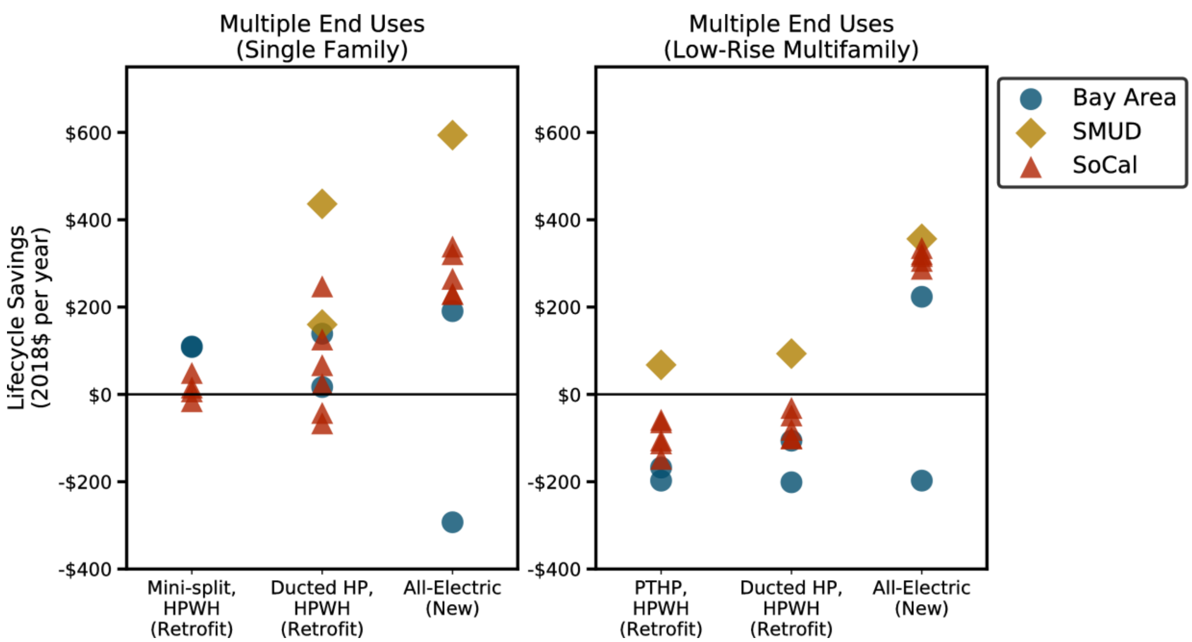
The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal).

3.4.5 MULTI-APPLIANCE RETROFITS (ELECTRIC HVAC AND HEAT PUMP WATER HEATERS) AND ALL-ELECTRIC NEW CONSTRUCTION

The lifecycle savings from electrifying both HVAC and water heating in retrofit applications are largely related to how much the appliances are used. In single family dwellings where there is a high demand for space heating, space cooling, and water heating, electrification of HVAC and water heating is more likely to deliver lifecycle savings, of up to $420 per year. In comparison, in low-rise multifamily dwellings, electrifying both HVAC and water heating would be more likely to incur lifecycle costs.

Electrification of an entire new construction home is analyzed as a package of measures (HVAC, water heating, cooking and clothes drying). Our results indicate that all-electric new construction delivers lifecycle savings relative to a mixed-fuel home with AC. The lifecycle savings of an all-electric new construction home are driven by the capital cost difference relative to a mixed-fuel home.

Figure 3-27 Lifecycle savings of electrifying multiple end uses, base case assumptions

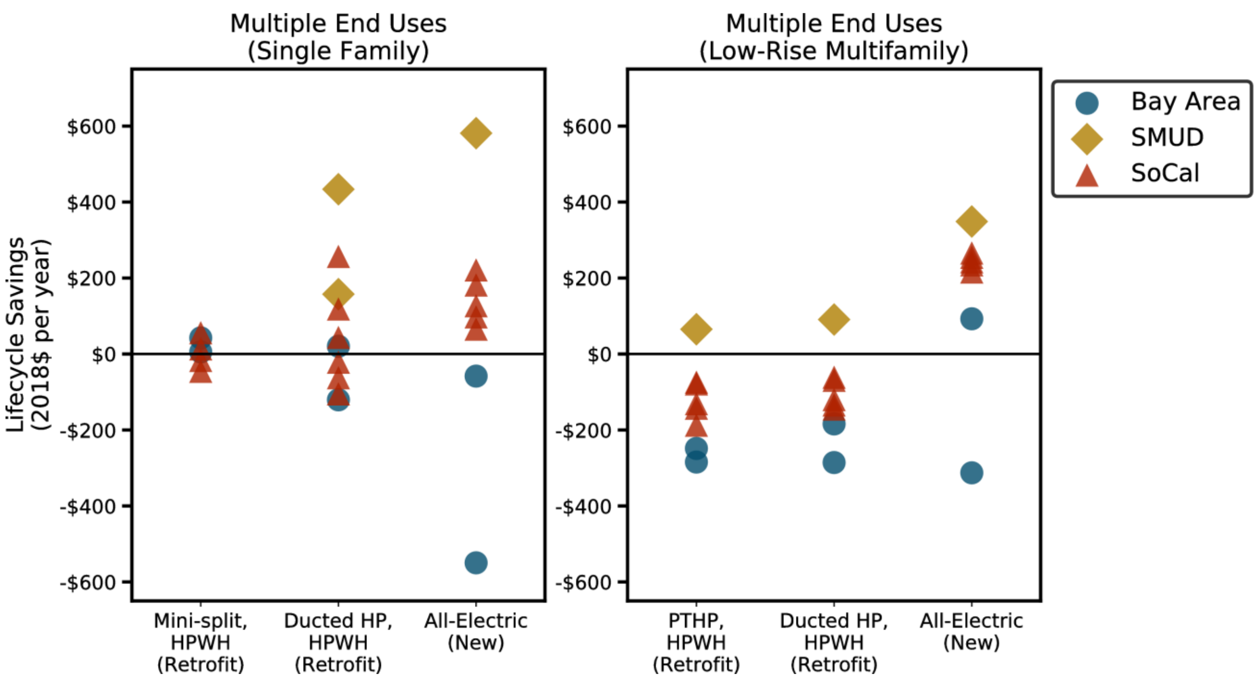


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal). Electrification of HVAC and water heating only is assumed for retrofit homes, and electrification of all end uses is assumed for new construction homes. Savings are relative to gas alternatives. Single family new construction homes have electric induction stoves and electric heat pump clothes dryers in addition to HVAC heat pumps and HPWHs. LRMF new construction homes have electric resistance cookstoves and electric resistance clothes dryers in addition to HVAC heat pumps and HPWHs. Positive values represent savings in both capital and operating costs throughout the lifetime of all appliances over the gas counterpart; negative values indicate lifecycle costs. Heat pump technologies here are the same as modeled for individual appliances above. The new construction blue dot (Bay Area) is an outlier here because in the gas baseline there is no air conditioning assumed.

Figure 3-28 shows the same set of lifecycle savings for a sensitivity case where electric rates are assumed to increase at the same pace as natural gas rates. Electric rates for PG&E, SCE, and LADWP are assumed to increase at the same annual rate of change as SoCalGas's gas rates (including a cumulative 32% increase above inflation from 2018 through 2022), and electric rates for SMUD are assumed to increase at the same annual rate of change as PG&E's gas rates (including a cumulative 6% increase above inflation from 2018 through 2022). In this sensitivity, PG&E's electric rates are assumed to increase faster than the natural gas rates due to wildfire risk and liability, while SCE's, SMUD and LADWP's rates are assumed to increase at the same pace at the gas utility in their service territory.

The lifecycle savings reflect the capital cost differences between electric and gas equipment, along with the electric rate sensitivity results as are shown in Figure 3-19. Under this electric rate sensitivity, lifecycle savings are lower overall, particularly in the PG&E (Bay Area) service territories, where the electric rates are assumed to increase more rapidly than the gas rates.

Figure 3-28. Lifecycle savings of electrifying multiple end uses, electric rate sensitivity

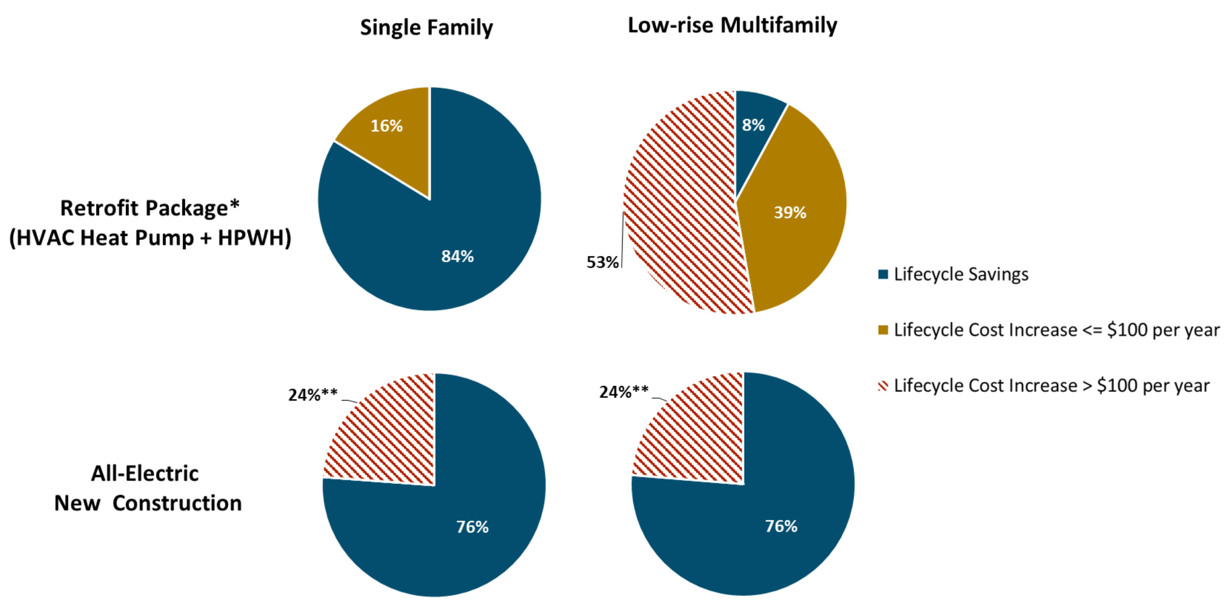


The multiple data points for each color represent the different climate zones in each area. Colors of the dots show the location of the modeled homes: the San Francisco Bay Area including CZ03 and CZ04 (Bay Area), Sacramento including CZ12 (SMUD), and Southern California including CZ06, CZ09 and CZ10 (SoCal). Electrification of HVAC and water heating only is assumed for retrofit homes, and electrification of all end uses is assumed for new construction homes. Savings are relative to gas alternatives. Single family new construction homes have electric induction stoves and electric heat pump clothes dryers in addition to HVAC heat pumps and HPWHs. LRMF new construction homes have electric resistance cookstoves and electric resistance clothes dryers in addition to HVAC heat pumps and HPWHs. Positive values represent savings in both capital and operating costs throughout the lifetime of all appliances over the gas counterpart; negative values indicate lifecycle costs. Heat pump technologies here are the same as modeled for individual appliances above. The new construction blue dot (Bay Area) is an outlier here because in the gas baseline there is no air conditioning assumed.

3.4.6 SUMMARY OF LIFECYCLE COSTS AND SAVINGS

The pie charts below summarize the key study findings, based on the share of homes in the study area that would see lifecycle savings, lifecycle cost increases of less than $100/year, or lifecycle cost increases of more than $100/year. By comparison, the Energy Information Agency estimates that US west coast households spend about $1500 per year on home energy expenditures.[51] The summary results below are calculated by scaling up our results to represent the current housing stock in the six studied climate zones in California.

Figure 3-29 Share of simulated households with lifecycle savings from adopting electric end uses; results are weighted by the estimated share of households in each climate zone and utility service territory

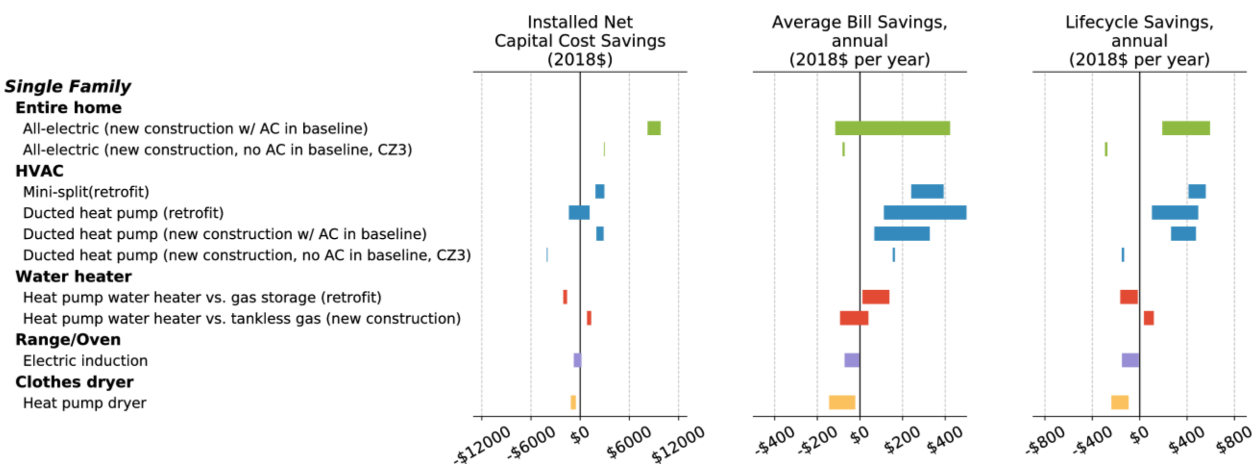


The building simulation results are weighted using the share of households in each combination of climate zone and utility, as described in section 2.2.1. to create this summary figure.
* We assume that all consumers in retrofit homes have or would install air conditioning in the mixed fuel baseline.
** This 24% of new construction that would not have lifecycle savings from electrifying the entire home correspond to buildings modeled in San Francisco (Climate Zone 3) that we assumed would not install air conditioning. For all new construction homes that include both air conditioning and space heating, electrifying all appliances shows lifecycle savings.

[51] https://www.eia.gov/consumption/residential/data/2015/c&e/pdf/ce1.5.pdf, based on the 2015 Residential Energy Consumption Survey (RECS). These expenditures include residential electricity and on-site energy use, but not household transportation.

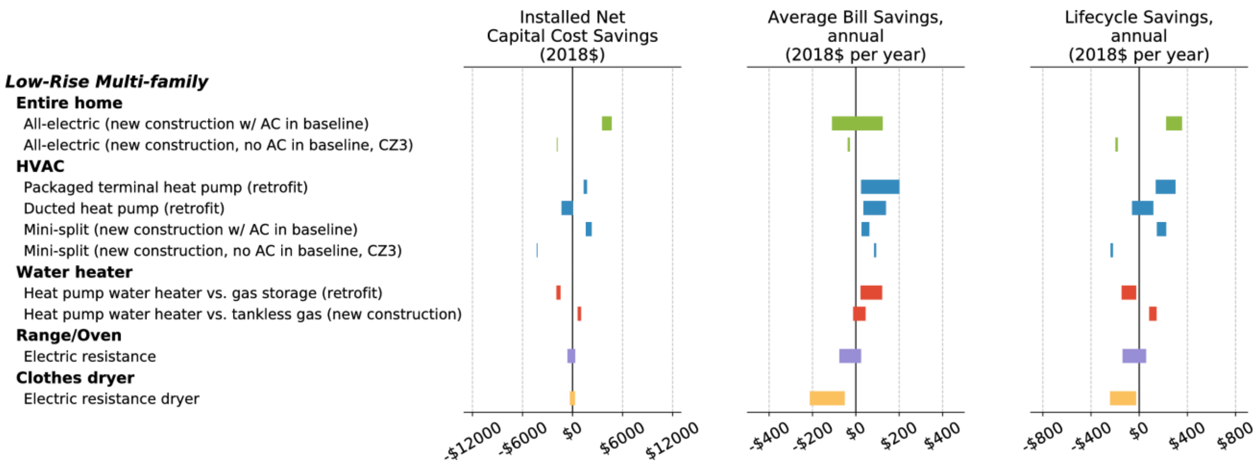
The cost results for single family and low-rise multifamily homes are summarized in each of the two figures below. The first column of results shows net capital costs or savings for installed electric equipment relative to natural gas equipment. The second column of results shows average annual bill savings for electric equipment relative to natural gas equipment. The third and final column shows net lifecycle savings of electric equipment relative to natural gas equipment.

Figure 3-30. Customer cost results for electrification in single family homes (cost ranges are due to variations by climate zone and utility rates)



Costs are relative to the gas baseline. Installed Net Capital Cost Savings are zero for the "All-electric (new construction, no AC in baseline, CZ3)" row.

Figure 3-31. Customer cost results for electrification in low-rise multifamily homes (cost ranges are due to variations by climate zone and utility rates)



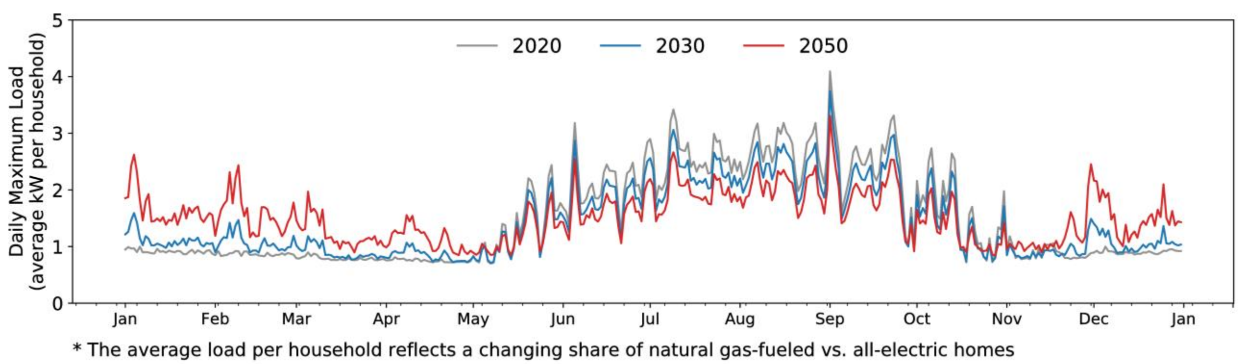
Costs are relative to the gas baseline.

3.5 Grid Impacts

To estimate the impacts of building electrification on the electric grid, we evaluated the peak demand of an average household under increasing levels of residential building electrification adoption in the study area. Compared to the reference low-electrification scenario, the high building electrification scenario results in slightly lower summer peak loads due to greater cooling efficiency with HVAC heat pumps. Although an increase in winter electricity demand is observed across all climate zones, this increased demand remains below summer peak demand levels under "typical" weather year conditions (Figure 3-32). (The temperature and weather assumptions are based on the California Energy Commission's Typical Meteorological Year (TMY) weather files used in the Title 24 building code.)

In California today, the grid is a summer peaking system. This means that the summer peak load is used to plan system-wide capacity additions and investments. One measure of the utilization of the electric grid is known as the load factor, which is simply the ratio of average energy consumption to peak demand. In 2018, the load factor for residential building loads in the study area is estimated at 19% using the study's building simulation data for mixed-fuel homes. Under a high building electrification scenario (described in section 2.7) the load factor is estimated to increase to 26% in 2050. This indicates that California's bulk grid infrastructure could be more fully and better utilized under a high-electrification future. It is important to note that this study does not evaluate local distribution-level impacts of residential building electrification, an area of research that may warrant further attention.

Figure 3-32: Daily average household maximum loads from electrifying all end uses in a high building electrification scenario



The average load per household is weighted by the share of households in the home types and climate zones within the study area. Temperatures are based on the typical meteorological year data from the CEC Title 24 code.

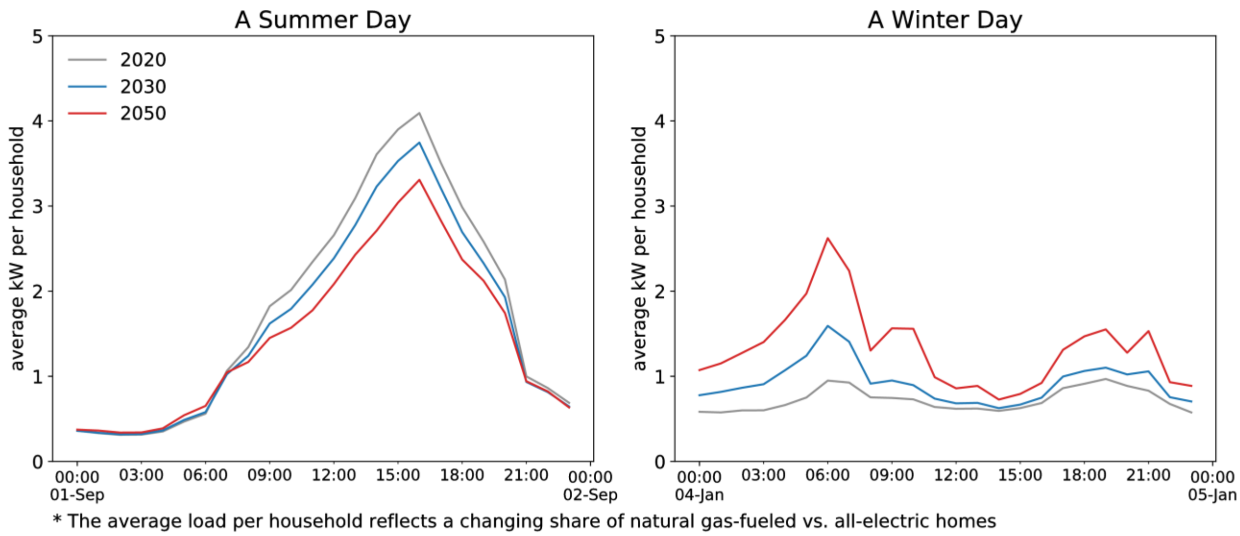
The weather data applied in this study represent typical rather than extreme conditions. Therefore, this estimated peak load does not capture worst-case conditions that system planning may consider. The average load presented here has some representation of climate zones, home types and vintages simulated in this study. However, the system-level load is likely to show less temporal variation than what is simulated here, due to diversity of building types and behavior patterns.

This analysis does not reflect the likely increase in air conditioning adoption due to climate change, or higher cooling demands and lower heating demands due to climate change. In general, the impacts of climate change will tend to reduce the future likelihood that California could become a winter-peaking system even under high electrification of space heating in the state.[52]

By further analyzing the diurnal characteristics of the average load, we find little change in load due to electrification on a hot summer day, with only a slight reduction in the peak due to more efficient cooling from high efficiency heat pumps compared to standard efficiency air conditioners (Figure 3-33). Overall, on a summer day, residential electric loads continue to be driven by space cooling needs. On a winter day in 2050, electric heating drives up the total electric load creating a morning peak and a second peak in the afternoon. However, under the typical meteorological year (TMY) weather conditions modeled here, the winter load is still smaller than the summer load both on average and on peak, even with all end uses electrified.

[52] While research continues to investigate the possibility of changes in the patterns of winter temperature extremes due to changes in jet stream dynamics (popularly known as the "polar vortex" phenomenon), basic climate science and model projections forecast even greater increases in annual minimum temperatures than annual mean temperatures (Collins et al. 2013), and annual minimum temperatures have been trending upward in North America (Krakauer 2018).

Figure 3-33 Hourly average household residential building load in a high electrification scenario: a summer and winter day

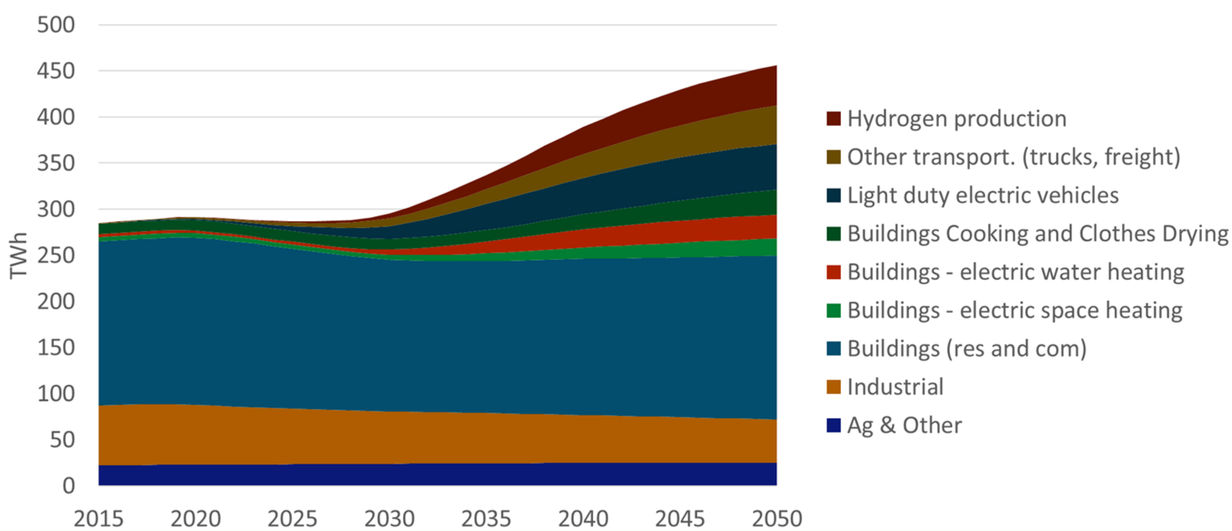


The average load per household is weighted by the share of households in the home types and climate zones within the study area.

This is a rough initial screen to determine whether electrification could exacerbate peak load impacts across the state. The impacts of load changes driven by electrification in specific locations and distribution systems were not analyzed in this study. In addition, we did not assess the difficulty of integrating these loads as the levels of variable renewable energy sources in the system increase. We would expect that summer cooling loads would be more easily integrated than winter heating loads because of their better coincidence with solar availability. Finally, we did not include some of the coldest climate regions in the state in this study, although these represent a small portion of California's households.

In terms of total electricity consumption, increasing demands from building electrification could be significant, but the total load growth is still likely to be smaller than the impact of transportation electrification in a high electrification, deep decarbonization future (Figure 3-34).

Figure 3-34 California electricity consumption in the CEC PATHWAYS High Electrification scenario



Source: Mahone, 2018

4 Discussion

This section includes discussion of results by appliance, drivers of differences in consumer economics, market adoption barriers, and further research needs. See the Executive Summary and Recommendations for a summary of the report's key conclusions and recommendations.

4.1 Building Electrification Consumer Economics for Individual Appliances and Electrification Packages

+ **All new construction homes and nearly all existing homes simulated in the study area that utilize air conditioning see lifecycle savings from an electric heat pump HVAC system.** In the California climate zones evaluated in this study, electrification of space heating is favorable because mild temperatures allow heat pump space heating to average ~4 to 6 times greater efficiency than natural gas furnaces, and bill savings are also seen from more cooling due to the use of high efficiency equipment. In homes without air conditioning, for which air conditioning is not planned, heat pumps are not expected to yield lifecycle savings due to the large incremental capital costs of expanded HVAC functionality, which can require ductwork, electrical work, and new compressor placement; ductless heat pumps are one option to reduce the magnitude of this incremental capital cost.
+ **Heat pump water heaters show capital cost savings for all of the new construction simulations, and bill savings for all of the simulated existing homes, yielding moderate net lifecycle savings for new construction and net costs for existing homes.** Heat pump water heaters in new construction had lower capital costs than gas tankless water heaters, but also showed relatively low bill savings compared to this relatively efficient gas option. Heat pump water heaters in existing homes showed bill savings compared to gas storage water heaters, but they had significantly higher capital costs. Very high efficiency water heaters and smart appliances with

flexible schedules (especially with compatible rate design) would yield improved bill savings in new construction, while low cost, retrofit-ready models could help with existing homes. Policy should target higher efficiency and flexible water heaters for new construction along with reducing the incremental capital cost of existing equipment for existing homes via incentives and market transformation. Incentivizing the installation of heat pump water heaters along with HVAC heat pump retrofits (discussed as a "retrofit package" below) could yield cost savings from the combination, with the potential for additional soft cost savings beyond what is modeled here from reducing the number of separate installation jobs.

+ **Most homes are not expected to see lifecycle savings from electric cooking and clothes drying given current rate structures, although most lifecycle cost increases were less than $100 per year for each appliance.** This is because of the relatively small efficiency benefits of electric cooking and clothes drying as compared with heat pumps (although they can still result in substantial GHG savings relative to natural gas cooking and clothes drying). The largest bill increases were seen for electric resistance clothes dryers; heat pump clothes dryers result in smaller bill increases but have higher capital costs and commonly available heat pump clothes dryer options in the U.S. may have inferior performance characteristics. Currently available induction stoves have higher capital costs than gas stoves in the U.S., but that is likely a function of the current market targeting induction as a high-end option. Low-cost portable induction burners are available in today's market, and induction stoves are cheaper in other countries, such as China, where they are more common. Induction may have non-economic advantages such as more precise cooking temperatures, easier cleanup, and superior health and safety profiles, but most customers remain unfamiliar with them relative to conventional electric resistance stoves. Despite unfavorable economics as individual appliance, electric cooking and clothes drying could still be part of a cost-effective all-electric package, by helping to avoid gas infrastructure and fixed bill charges for natural gas (discussed below).

+ **All-electric new construction sees lifecycle savings in all homes that require air conditioning, based on large capital cost savings and small net changes in bills for most homes.** Capital cost savings are driven primarily by savings from the HVAC system and avoided gas infrastructure, and were found for all homes modeled as containing central air conditioning in the baseline mixed fuel home. Under current rate structures, and current equipment efficiencies, all-electric new construction has mixed results for energy bills compared to a natural gas alternative, with bill savings from HVAC tending to be offset by bill increases for electric cooking and clothes drying. The installation of "best of class" heat pump water heaters and heat pump HVAC systems would allow bill savings in most regions and home types, and could still yield lifecycle savings, even though they have higher capital costs than commonly available heat pump equipment. Because of this, policy should encourage very high efficiency appliances for all-electric new construction. New construction without air conditioning was evaluated as an option in the Bay Area climate zone; there, all-electric new construction was not found to result in cost savings if the reference home did not have air conditioning.

+ **All existing homes modeled would see bill savings with a retrofit package combining a heat pump water heater and a heat pump HVAC.** Bill savings are found for both HVAC and water heating individually when compared to the baseline mixed fuel home. Capital cost savings for HVAC also occur for most home types and vintages when replacing both a gas furnace and air conditioner with a heat pump, and these can help to offset capital cost increases for water heating. Electrical panel upgrades may be needed for some older homes that reduce capital cost savings or lead to capital cost increases. Overall, lifecycle savings occur for nearly all single family homes, while most low-rise multifamily homes do not see lifecycle savings because lower HVAC energy demands provide less opportunity for bill savings to offset capital cost increases. Because bill savings already occur for all home types we modeled, policy should be targeted at alleviating incremental capital costs via incentives or market transformation. We only simulated existing homes that include AC in the baseline gas-fueled home, but we do not expect lifecycle savings would occur for homes lacking AC due to the large capital cost increases associated with retrofitting the HVAC functionality to allow air conditioning with a heat pump.

4.2 Understanding Drivers of Differences in Consumer Economics

Within the same electrification and home categories, we identified five major predictors of differences in net lifecycle costs, detailed below.

1. **Heat pump HVAC is more cost-effective in homes with central air conditioning units**. A big factor in the cost-effectiveness of heat pump HVAC retrofits is the presence of central AC. Homes that already have AC or that would benefit from an AC upgrade can generally save money by installing a ducted heat pump (if central ducting is already present) or a ductless system (if no central AC or ducting is present), because of the benefit of displacing two appliances (a gas furnace and AC). In contrast, for older homes that do not currently have AC and the owners do not want AC, the cost of new ducting, placement of a compressor, and/or new electric wiring can make the retrofit for heat pump HVAC prohibitively expensive.

2. **Displacement of gas infrastructure (new construction only)**. An important factor in the cost-effectiveness for all-electric, low-rise residential new construction is the value of avoided gas infrastructure both within the home and connecting to the distribution system. Note that we only considered gas infrastructure costs that are typically borne by the builder, not the full infrastructure costs including utility costs. If these costs were included in the analysis, or if future regulatory changes required these costs to be considered in cost-effectiveness analysis, or directly passed onto builders, the capital cost savings for all-electric new construction would likely be significantly larger.

3. **Heating and cooling demands**. Smaller and better-insulated homes with lower heating and cooling requirements tend to have less potential for bill savings from electrification of HVAC to offset any incremental capital costs of electrification packages. However, capital cost savings can still drive lifecycle savings in these homes due to the displacement of two appliances (#1 above) or avoided gas infrastructure (#2 above).

4. **The capacity of the existing electrical panel (retrofits only)**. This analysis finds that in existing homes that require an electrical panel upgrade in order to electrify both HVAC and water heating, the cost-effectiveness of electrification is significantly reduced. Unfortunately, there is not good data available about the prevalence of homes with less than 200 amp electrical service, so it is difficult to estimate the precise number of homes in California for which this might be a challenge, although it is expected to be a minority of homes and to decline over time. Developing "retrofit-ready" heat pumps with lower current requirements could be an important technology innovation to allow more wide-spread adoption of electrification technologies in older, pre-1990s vintage homes.

5. **Electricity rates and rate design**. Not surprisingly, the electricity rate is of critical importance for determining the cost-effectiveness of electrification for consumers. SMUD enjoys some of the lowest electricity rates in the state, and as a result nearly always showed significant bill savings from electrification, reaching more than $600 per year in some cases. In contrast, the other utilities evaluated have higher overall rates, so tended to show less bill savings or net bill costs resulting from electrification. The utilities vary in the extent to which rate designs incorporate fixed costs into volumetric rates rather than fixed charges, which also has an impact on the cost-effectiveness of electrification. However, the implications of these rate design choices are not isolated in this analysis from the overall effects of electricity rates on cost-effectiveness.

4.3 Market adoption barriers

Even when households would save money by switching to electric heat pumps and other appliances from gas appliances, a number of market barriers and market failures act as hindrances to widespread adoption. A broad list of electrification barriers and potential solutions is included in Appendix D: Market Adoption Barriers and Potential Solutions.

Market barriers fall into several key categories: consumer market failures, supplier market failures, and policy misalignment. Consumer market failures include imperfect information, transaction costs, limited access to credit, split incentives, and bounded rationality.[53] These can be addressed with consumer-facing incentives, education and outreach campaigns, and low-cost financing. Supplier market failures include lack of contractor familiarity with electric options and principal-agent problems[54], which can be addressed with contractor training, trusted contractor lists, utility direct install programs, upstream / contractor-facing incentives, and better targeting of code enforcement. Policy misalignment includes lack of regulatory support for fuel-switching incentives and tiered electric rates: incentives for fuel-switching and efficiency should be simplified and aligned with the goal of GHG savings, and rate designs should avoid penalizing electrification or collecting fixed costs via volumetric rates. We note the importance of not unduly burdening low income households when changing rates to make them more efficient and supportive of climate goals. Any new rate design effort would require careful analysis, building on existing research.[55] More detailed policy recommendations are discussed below.

4.4 Further Research Needs

Below we suggest areas for additional research, which could build on the work presented in this analysis:

+ Investigate the benefits of HVAC flexible dispatch to minimize coincidence with peak TOU periods.
+ Develop a better quantification of the avoided natural gas infrastructure costs associated with all-electric new construction.

[53] See, e.g., Dietz et al. (2009), Sallee (2014), Gillingham and Palmer (2014).
[54] See Blonz (2018).
[55] Several recent articles highlight problems with existing rate design and opportunities for improvement (Burger et al. 2019; Lo et al. 2019; Borenstein and Bushnell 2018). Burger et al. (2019) notes that a simple move to fixed charges and TOUs could have economically regressive impacts, but there are straightforward solutions, such as making fixed charges a function of income or strong correlates of income.

- Evaluate electricity system costs and savings, particularly at the distribution system level, resulting from the combined impact of building and vehicle electrification.
- Investigate the impediments to increasing rates of new construction and building upgrades, including building electrification.
- Develop a better understanding of the drivers of building electrification retrofit capital costs across regions, including a better understanding of how many homes, and of what types, may require an electrical panel upgrade to enable electrification.
- Evaluate the customer costs and benefits, and societal costs and benefits of building electrification in the climate zones not evaluated in this study, including colder Northern and mountainous climate zones.
- Evaluate cost-effective electric solutions for multi-family high-rise and mixed-used high-rise buildings, which are a growing share of the California housing stock but have highly heterogeneous characteristics.
- Develop a better understanding of the challenges of maintaining reliability and resiliency with electrification of critical household end uses in the context of increasing vulnerability to wildfires and other extreme events related to climate change.
- Develop a framework to make electric rates more economically efficient and supportive of climate goals while not burdening low income customers or introducing new inefficiencies, building on existing research (Burger et al. 2019; Lo et al. 2019; Borenstein and Bushnell 2018).

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6 Appendix A: Technology Characterization and Screening

6.1.1 INTERNATIONAL MARKET FOR HEAT PUMPS

Electrified heating represents a significant and growing market share in certain European and Asian markets; primarily in regions with energy security, climate, or air quality concerns. Japan, Germany, and Sweden have focused policy attention on increasing the deployment of heat pumps to reduce dependence on imported fossil fuels and greenhouse gas emissions. Policy efforts there have focused primarily on incentives and incorporating electric heat into building codes for new construction, as well as testing and performance standards to ensure quality and build consumer confidence in heat pump technology[56].

6.1.1.1 Japan

Japan began pursuing air source heat pumps in the mid-1990s as part of a broader efficiency and fuel switching strategy intended to reduce the country's reliance on fossil imports. Consequently, heat pumps have taken a significant share of the total heating market, with about 140 million cumulative installations of air source heat pumps in homes and commercial buildings[57]. Japan appears to be at the forefront of high efficiency heat pump technology development today, with many high efficiency products available in Japan that are not currently available in the United States, such as compressed carbon dioxide heat pump water heaters. For example, the EcoCute is a high-efficiency, carbon dioxide heat pump water heater promoted by government agencies to reduce energy demand for water heating – approximately

[56] See Hanna, Parrish, and Gross (2016)
[57] See Shibata (2011)

30% of all household energy demand. The use of carbon dioxide as a refrigerant in the EcoCute is part of a focused effort in Japan to eliminate the use of high-GWP refrigerants common in most residential and commercial heat pumps. Currently at least one manufacturer, Sanden, is selling these heat pump water heaters in the United States market, although they are not expected to achieve a large market penetration because of their high cost[58].

6.1.1.2 China

China has the world’s largest market for electric heat pumps, with 40 to 50 million air source heat pumps sold annually[59]. Heat pumps, as well as natural gas furnaces, have been aggressively promoted in some provinces as a key strategy to mitigate urban air quality concerns associated with the open burning of coal common in residential and commercial buildings. The electrification campaign, focused primarily in Beijing and other northern provinces, has coincided with efforts to expand and modernize local electric and natural gas distribution systems, and has often been followed by local ordinances prohibiting the use of coal for heating[60]. Given China’s growing population and strong policy directives, this market is expected to drive innovation and cost reductions in heat pump technologies over the coming years.

6.1.1.3 European Markets

A combination of policy and economic conditions have created a robust market for electrified heating in certain European jurisdictions, particularly northern and central Europe: these regions share cold winters, high natural gas prices, and favorable policies. These markets began to see significant adoption of early heat pump technologies in the 1970s, following periods of energy security and energy price concerns, and have

[58] See Gluesenkamp et al. (2017)
[59] See Zhao, Gao, and Song (2017)
[60] See Myers (2018)

seen renewed interest as European governments have introduced new policies to address carbon emissions in recent decades.

In 2017, electric heat pumps eclipsed gas heating in residential buildings in Germany for the first time, with 43% of buildings heated by air or ground source heat pumps[61]. In Switzerland, approximately 75% of new homes were built with electric space and water heating, while in Scandinavia, heat pumps have become the dominant heat source in Finland[62] and are a growing share of Sweden's electrical heating market[63].

6.1.2 MANUFACTURING AND HISTORY

Consistent with a significant, established international market that overlaps with the manufacturing of air conditioning, the heat pump manufacturing market is large and diverse. There are a broad range of both multinational and regional vendors, primarily consisting of manufacturers of air conditioners and other durable consumer goods. Major manufacturers of heat pumps include A.O. Smith (US), Carrier (US), Daikin (Japan), Danfoss (Denmark), Mitsubishi and Fujitsu (Japan), and NIBE (Sweden).

Carrier and A.O. Smith, the primary US-headquartered manufacturers, offer a broad range of residential and commercial air-to-air, ground-to-air, and air-to-water heat pumps using conventional refrigerants. Additionally, foreign manufacturers like Mitsubishi, Fujitsu and Daikin have developed extensive distribution and installer networks in the US for their heat pumps products.

[61] See https://www.coolingpost.com/world-news/heat-pumps-overtake-gas-in-germany/
[62] See https://www.sulpu.fi/documents/184029/189661/The%20future%20of%20Heat%20Pumps.pdf
[63] See http://www.varmemarknad.se/pdf/The_heating_market_in_Sweden_141030.pdf

6.1.3 HEAT PUMP PERFORMANCE AND COLD CLIMATE HEAT PUMPS

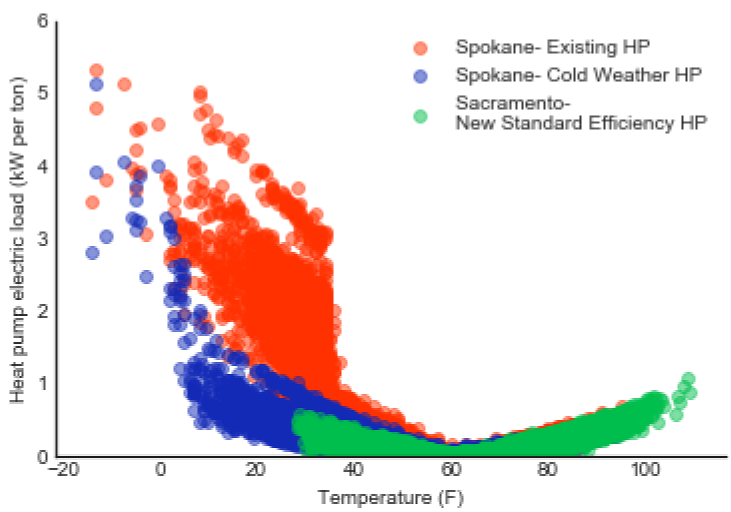
Heat pumps function using the same principles as a refrigerator or an air conditioner. They transfer heat between two systems – for example, extracting heat energy from outdoor air and delivering it as warm air inside a residential building. Because heat pumps transfer heat, rather than converting it directly from chemical or electrical energy, they can deliver useful heat energy in quantities considerably greater than the energy required to operate them. This ratio of input energy to output energy is often measured as the Coefficient of Performance (COP). (COP is defined as the annual average performance, and it can be compared with an efficiency by multiplying by 100; i.e., a COP of 4.0 means an annual average efficiency of 400%.)

Electric air source heat pump space heating technologies range from about 200% to more than 400% efficient, depending on the temperature differential between indoors and outdoors: they heat more efficiently at warmer temperatures. In contrast, high efficiency natural gas furnaces achieve 90% efficiency, while electric resistance heating is approximately 100% efficient. For US markets, the Department of Energy's 2015 appliance efficiency standards effectively mandate minimum seasonal COP of 2.5 for heating and 4.1 for cooling based on a specified set of temperature conditions (the heating seasonal performance standard minimum requirement is 8.2).

Heat pump space heating technology was first widely deployed during the 1970s; however, these early generation technologies were not particularly efficient, and relied heavily on supplemental heat in colder temperatures, such as electric resistance backup heat, often resulting in high winter electric bills for their owners. Heat pump failures and service issues were significant factors in the stagnation of the heat pump industry, leading to industry and policy efforts to improve product and installation quality. However, heat pump efficiency improved considerably in the 1990s, paving the way for a resurgence in the heat pump market in the 2000s.

Similarly, heat pump performance has improved considerably in cold climates, which represent a challenge for older technology single-stage HVAC heat pumps. Using improved compressor technology and improved refrigerants, modern heat pumps can maintain efficient output at much lower ambient temperatures, enabling their use in much colder climates such as the US Midwest and Northeast. Much of this heat pump research has occurred in Northern Europe and Japan, which hosts a range of climate zones, including colder Northern regions with average winter low temperatures below -10°C/10°F, where traditional heat pumps were initially unsuitable. Variable-speed (inverter-driven) compressors are one approach to allowing colder temperature operation and enhancing efficiency across the temperature range, that also provide benefits such as reduced noise and improved comfort.

Figure 6-1. Relationship between outdoor temperature and heat pump electric load



Note that “ton” in this figure refers to the tonnage, or power, of the heat pump. Energy usage of the heat pumps in this data was divided by the tonnage of the heat pumps to arrive at kW per ton.

Ductless heat pumps are another recent innovation that have a large market share in Asia and are beginning to enter the US market. They include small, modular indoor and outdoor units connected by thin refrigerant pipes. In compact houses or apartments lacking existing ducting, they can be an inexpensive option that also allow very high efficiencies because energy is not lost in ventilation and ducting.

6.1.4 THE GREENHOUSE GAS IMPLICATIONS OF REFIGERANT USE IN HEAT PUMPS

Heat pumps utilize refrigerants, typically in a vapor-compression cycle to transfer heat. Ideal refrigerants have many requirements, including an appropriate boiling point and thermal properties as well as low toxicity and flammability. Unfortunately, like refrigerators and air conditioners, heat pumps originally relied on refrigerants with detrimental environmental impacts. Chlorofluorocarbons (CFCs) were popular throughout the mid-twentieth century but were recognized as ozone depleting and so were phased out beginning in 1987 with the Montreal Protocol.

Replacement refrigerants, such as hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs), while presenting a much lower risk for atmospheric ozone depletion than chlorofluorocarbons (CFCs), still have significant global warming potentials, in some cases thousands of times the global warming potential of carbon dioxide by mass. When these gases escape into the atmosphere, through leaks, accidents, or improper disposal, they contribute to global climate change. As a result, there is growing interest in identifying alternative refrigerants.

The first widespread implementation of a very-low-GWP refrigerant, introduced in a heat pump water heater in 2001 in Japan, was compressed CO_2, which in addition to its low-GWP attributes provides improved performance in many heat pump applications. Having a global warming potential of 1, CO_2 has orders of magnitude lower climate impact than the refrigerants most commonly used today for this application. It has emerged as a promising refrigerant for commercial HVAC heat pumps as well as for heat pump water heaters due to its higher efficiency and ability to reach higher temperatures than other refrigerants, important for water heating applications[64]. However, because of its lower boiling point and thus higher operating pressure, it requires stronger, more expensive materials and construction, reducing the cost-effectiveness of its use in small applications such as residential heat pumps. Thus far, high-pressure CO_2 systems remain limited to water heating, for domestic hot water or for hydronic space heating, and non-residential applications: no air-to-air heat pumps for space heating have been developed.

Other very-low-GWP refrigerants that are currently being researched include ammonia, and hydrocarbons such as isobutane, propane, and olefins. Olefins represent a relatively lower pressure alternative to compressed CO_2, which may be cost-effective in residential applications[65]. The principal issue with using hydrocarbons as refrigerants is that they are flammable.

The most promising set of refrigerants in the near term is those that are chemically similar to refrigerants currently used, but that have a significantly lower global warming potential. For residential air-to-air heat pumps, the most likely near-term replacement refrigerant is R32 (GWP 675), which would replace R410A (GWP 2088)[66]. Development of low-GWP refrigerants such as R32 is an area of active research.

When an air conditioner using today's refrigerants is replaced with an HVAC heat pump, there is no additional refrigerant leakage risk, assuming the heat pump system has a similar tonnage. A home's refrigerant leakage risk will only increase if an HVAC heat pump is installed when there was previously no air conditioning. There is an increased refrigerant leakage risk when switching to heat pump water heaters and heat pump clothes dryers, but the resulting increase in average greenhouse gas emissions is dwarfed by the savings in emissions from not using natural gas, as seen in Figure 1-1: Annual GHG emissions from

[64] See Nekså et al. (1998)
[65] See Watanabe et al. (2017)
[66] See California Air Resources Board (2017)

a mixed-fuel and all-electric 1990s vintage home in Sacramento and Figure 3-1: Annual GHG emissions from a 1990s vintage single family home for Sacramento.

6.1.5 ELECTRIC RESISTANCE AND INDUCTION STOVES

Induction cooktops have several advantages over gas and electric resistance stoves, principally efficiency and safety. Induction cooking is modeled using an efficiency of 84% (0.74 energy factor for the cooktop), compared to 74% for electric resistance and 40% for gas. Unlike electric resistance stoves, induction stoves can be controlled almost instantaneously, similar to gas stoves.

Induction cooktops are popular in Europe and Asia but have not seen widespread adoption in the United States market. Some cooks value induction stoves for their safety (they do not burn to the touch, since they operate based on electromagnetism) and the precise level of temperature control offered by induction stove. Induction stove are generally slightly more expensive than comparable electric resistance cooktops in the US market, but this appears to be more a function of limited market share, that targets higher-end products, rather than inherent engineering expense, as cheap portable versions are available and popular in markets outside the U.S. At current prices, the markup on an induction stove is generally not recouped through energy savings over the lifetime of the unit. Additionally, aluminum cookware, which is very common in the United States, is not compatible with induction stoves. Switching to induction stoves requires cookware that is magnetic, such as cast iron or stainless steel, which may present an adoption barrier for some consumers. These cost factors, along with consumers' lack of familiarity with induction stoves, represent barriers to widespread adoption. Despite these barriers, induction stoves are a promising alternative to electric resistance stoves, and may become acceptable, or even preferred, by consumers accustomed to gas stoves.

6.1.6 HEAT PUMP CLOTHES DRYERS

Heat pump clothes dryers are relatively common in some European countries but have not yet become widespread in the United States. Heat pump clothes dryers are about 50% more energy efficient than natural gas clothes dryers and are about 35% more efficient than electric resistance clothes dryers. However, there are significant performance limitations with currently available models: they may take longer to dry and require more maintenance.

6.2 Overview of Technology Selection and Efficiencies

6.2.1 HEATING, VENTING AND AIR CONDITIONING (HVAC)

Table 6-1 Electric HVAC system selection

	Single-Family	Low-Rise Multifamily
Retrofit (Pre-1978s)	• Electric: Non-ducted mini-split heat pump • *Gas: replaces wall furnace with ducted furnace and AC*	• Electric: Packaged terminal heat pump (PTHP) • *Gas: new wall furnace and window AC*
Retrofit (1990s)	• Electric: Ducted split heat pump • *Gas: replaces ducted furnace with new ducted furnace and AC*	• Electric: Ducted heat pump • *Gas: Combined hydronic system + AC*
New Construction	• Electric: Ducted split heat pump • *Gas: replaces ducted furnace with new ducted furnace and AC* (CZ3: no AC)	• Electric: Ducted mini-split heat pump • *Gas: ducted furnace and AC* (CZ3: no AC)

6.2.1.1 Single family

Table 6-2 Efficiencies of HVAC systems selected for single family homes

Home Type	Equipment	Modeled Efficiency
Mixed Fuel, all vintages	Furnace	80 AFUE ducted attic furnace
Mixed Fuel, all vintages	Split air conditioner	14 SEER, 12.2 EER, 2-speed
All Electric, new construction, 1990s vintage and pre-1978 vintage (CZ10 and CZ12)	Ducted split heat pump	18 SEER, 14 EER, 10 HSPF, 2-speed
All Electric, pre-1978 vintage (CZ03, CZ04, CZ06 and CZ09)	Non-ducted mini-split heat pump	21 SEER, 13 EER, 11 HSPF

6.2.1.1.1 Case 1, 2, & 3: Ducted split heat pump

For single family homes, ducted split heat pumps were selected to replace ducted furnaces with split air conditioners or ducted furnaces alone without cooling. Ducted split heat pumps are a very mature technology with a large range of efficiency options.

6.2.1.1.2 Case 3: Non-ducted mini-split heat pump, multi-head

For pre-1978 existing single family homes, where the basecase system is a non-ducted gas wall or floor furnace and either a window air conditioner or no cooling system, a non-ducted mini-split heat pump (MSHP) with multiple indoor units was selected as the electric replacement. This basecase system is inexpensive and easy to replace but suffers from low performance and does not provide equivalent comfort conditions as a distributed heating/cooling system. Converting to a ducted system is expensive and MSHPs offer a practical alternative for less cost. Electric single point heating/cooling options such as a MSHP with a single indoor unit may be relatively affordable but compromises comfort and if the electric alternative system does not provide reasonable levels of comfort, there is a risk that the technology will not be accepted. In smaller multifamily homes this trade-off may be acceptable but not in single family homes or larger multifamily. For this case the base case gas replacement assumes conversion to a ducted furnace in order to provide similar comfort conditions across the gas and electric options.

6.2.1.2 Low-rise Multifamily

Table 6-3 Efficiencies of HVAC systems selected for low-rise multifamily homes

Home Type	Equipment	Modeled Efficiency
Mixed Fuel, all vintages	Furnace	80 AFUE ducted attic furnace
Mixed Fuel, all vintages	Split air conditioner	14 SEER, 12.2 EER, 2-speed
All Electric, new construction	Ducted mini-split heat pump	21 SEER, 13 EER, 11 HSPF
All Electric, 1990s vintage	Ducted split heat pump	18 SEER, 14 EER, 10 HSPF, 2-speed
All Electric, pre-1978 vintage	Packaged terminal heat pump	11 EER, 3.3 COP

6.2.1.2.1 Case 4: Ducted mini-split heat pump

For new low-rise multifamily home construction, a ducted mini-split heat pump (MSHP) was selected to replace ducted furnaces with split air conditioners or ducted furnaces alone without cooling. While costs are higher than traditional split heat pumps; MSHPs are most appropriately sized for the low cooling and heating loads expected in small, new construction apartments. MSHPs are already becoming more common in the multifamily market.

6.2.1.2.2 Case 5: Ducted split heat pump

For existing low-rise multifamily units with a single gas water heater providing both space and water heating, coupled with a split air conditioner (depending on climate), ducted split heat pumps were selected as the electric replacement. While a hydronic distribution system with a HPWH would be the most direct replacement option, prior experience has shown that residential HPWHs on the market do not have the capacity to serve both the space and water heating loads without reverting to electric resistance mode. An alternative option would be a larger capacity air-to-water heat pump with a storage tank replacing the water heater. However, there are few products available today and market readiness is lower.

6.2.1.2.3 Case 6: Packaged terminal heat pumps

For pre-1978 existing low-rise multifamily units with a wall or floor furnace and either a window air conditioner or no cooling system, a packaged terminal heat pump (PTHP) was selected as the electric replacement. Similar to Case 3, there is potential comfort issues for any apartments except studios with open floor plans (no rooms with closeable doors) by not providing conditioned air to each room. While comfort issues may arise from a single zone PTHP, the replacement system can provide equivalent or better comfort than the replacement gas equipment and window AC. The incremental cost of other systems such as multi-head MSHPs is more difficult to justify given the low loads of small apartments.

6.2.2 WATER HEATING

Table 6-4 Efficiencies of water heating systems selected for single family and low-rise multifamily homes

Home Type	Equipment	Modeled Efficiency
Mixed Fuel, retrofits	Gas storage water heater	0.63 UEF (0.60 EF) 1900s vintage in garage, 1970s vintage in home
Mixed Fuel, new construction	Gas tankless water heater	0.81 UEF (0.82 EF) in garage
All Electric, all vintages	Heat pump water heater	3.0 EF, NEEA Tier 3 new construction and 1990s vintage in garage, 1970s vintage in home

6.2.3 OTHER APPLIANCES

Table 6-5 Electric cooking and clothes drying selection

	Single-Family		Low-Rise Multifamily	
Cooking & Clothes Drying (All vintages)	HEAT PUMP DRYER	INDUCTION STOVE	ELECTRIC DRYER	ELECTRIC STOVE

Table 6-6 Efficiencies of selected appliances

Appliances	Case	Efficiency	Features/Notes
Cooking	Gas	Cooktop: 0.4 Energy Factor Oven 0.058 Energy Factor	
	Electric resistance (LRMF)	Cooktop: 0.74 Energy Factor Oven 0.11 Energy Factor	
	Electric induction (Single Family)	Cooktop: 0.84 Energy Factor Oven 0.11 Energy Factor	
Clothes Dryer	Gas	2.75 Energy Factor	
	Electric resistance (LRMF)	3.1 Energy Factor	
	Electric heat pump (Single Family)	4.2 Energy Factor	Moisture sensor
Clothes Washer	All	1.41 MEF	3.5 ft3 drum
Primary Refrigerator	All	Single Family: 15.7 EF (all) LRMF: 14.1 EF (existing homes) 17.6 EF (new construction)	Single Family: 25 ft3 side-by-side refrigerator LRMF: 18 ft3 top freezer refrigerator
Secondary Fridge/Freezer	All	Single Family: mix of efficiency LRMF: none	Single Family: energy use reduced based on a national average of 22.1% saturation for fridge and 34.2% for freezer
Dishwasher	All	318 Rated annual kWh per Energy Guide	8 place settings
All simulation parameters and schedules are based on NREL's BEopt and the House Simulation Protocols			

7 Appendix B: Building Simulation Descriptions

Thermostat Schedules as Modeled

The project team evaluated thermostat schedules to use in the modeling for the electrification study. The project team initially considered using the CEC Title 24 thermostat schedules for single family and low-rise residential buildings for the analysis, however, these schedules were ultimately not used in this analysis for the reasons described below.

A literature review considered the following sources:

+ 2004 SCE report: Programmable Thermostats Installed into Residential Buildings: Predicted Energy Savings Using Occupant Behavior & Simulation
+ 2017 SCE Work Paper SCE17HC054: Residential Smart Communicating Thermostat
+ 2016 Nest Labs report: Supplemental Data for California Smart Thermostat Work Paper
+ 2014 Building America House Simulation Protocols
+ 2016 Residential and Nonresidential Alternative Calculation Method Reference Manual
+ 2011 DOE report: U.S. Department of Energy Commercial Reference Building Models of the National Building Stock

Based on data reviewed, the project team developed the setback schedule in Table 7-1 for use in this project. This schedule assigns specific, rational times to the temperature changes and a 3°F temperature setback in winter and setup in summer (rounded to the nearest degree). The residential Title 24 thermostat schedule also uses a 3°F heating night setback but no daytime setback. Weekend/weekday schedules are likely to vary if the house is unoccupied during the day, but data from the Residential Appliance Saturation Study (RASS) supports using a daytime setback. The 76°F cooling and 70°F heating setpoint are closely aligned with the Building America settings.

Table 7-1: Thermostat Setup/Setback Schedules Used in this Analysis

	Cooling	Heating			Cooling	Heating
12:00 AM	79	67		12:00 PM	76	67
1:00 AM	79	67		1:00 PM	76	67
2:00 AM	79	67		2:00 PM	76	67
3:00 AM	79	67		3:00 PM	76	68
4:00 AM	79	68		4:00 PM	76	69
5:00 AM	79	69		5:00 PM	76	70
6:00 AM	79	70		6:00 PM	76	70
7:00 AM	79	70		7:00 PM	76	70
8:00 AM	76	67		8:00 PM	76	70
9:00 AM	76	67		9:00 PM	76	70
10:00 AM	76	67		10:00 PM	79	67
11:00 AM	76	67		11:00 PM	79	67

The shaded areas in the table above correspond to when systems are set back in winter and up in summer (or turned off). For heating, the temperature ramps up between 4 AM and 6 AM, and between 3 PM and 5 PM to limit strip heat operation. Although the ramp-up is not needed for base case systems, when applied to both it ensures building loads are the same for both cases.

For new homes the temperature may not drift more than 3°F between setup/setback periods and systems will be minimally active during these periods. For older leakier homes, systems will likely be working to maintain the setpoints.

Other thermostat scheduled evaluated

Table 7-2 summarizes Title 24 and other available thermostat schedules. Title 24 schedules include uncharacteristic setbacks and are different for low-rise and high-rise residential buildings. The differences reflected in the residential and non-residential schedules are not based upon actual differences based on occupancy but independent development of residential and non-residential compliance models.

Table 7-2: Title 24, Building America, and DOE Thermostat Schedules[67]

	Residential ACM[1]		Non-Res ACM Residential Living[2]		Building America House Simulation[3]		DOE Comm. Ref. Bldg. Models[4]	
Hour	Cooling Setpoint	Heating Setpoint	Cooling Setpoint	Heating Setpoint	Cooling Setpoint	Heating Setpoint	Cooling Setpoint	Heating Setpoint
1	78	65	78	60	76	71	75	70
2	78	65	78	60	76	71	75	70
3	78	65	78	60	76	71	75	70
4	78	65	78	60	76	71	75	70
5	78	65	78	60	76	71	75	70
6	78	65	78	60	76	71	75	70
7	78	65	78	68	76	71	75	70
8	83	68	78	68	76	71	75	70
9	83	68	78	68	76	71	75	70
10	83	68	78	68	76	71	75	70
11	83	68	78	68	76	71	75	70
12	83	68	78	68	76	71	75	70
13	83	68	78	68	76	71	75	70
14	82	68	78	68	76	71	75	70
15	81	68	78	68	76	71	75	70
16	80	68	78	68	76	71	75	70
17	79	68	78	68	76	71	75	70
18	78	68	78	68	76	71	75	70
19	78	68	78	68	76	71	75	70
20	78	68	78	68	76	71	75	70
21	78	68	78	68	76	71	75	70
22	78	68	78	68	76	71	75	70
23	78	68	78	60	76	71	75	70
24	78	65	78	60	76	71	75	70

The Title 24 low-rise residential thermostat schedules assume a 78°F and 68°F cooling and heating setpoints, respectively, with a setback/setup assumption. A 65° heating setback is used, while the cooling set up is as

[67] Sources: Table 19 of Residential Alternative Calculation Method Reference Manual (https://www.energy.ca.gov/2015publications/CEC-400-2015-024/CEC-400-2015-024-CMF-REV3.pdf), Appendix 5.4B of Non-Residential Alternative Calculation Method Manual (http://www.energy.ca.gov/title24/2016standards/ACM_Supporting_Content//), 2014 Building America House Simulation Protocols (Section 2.4) (https://www.nrel.gov/docs/fy14osti/60988.pdf), U.S. DOE Commercial Reference Building Models of the National Building Stock (https://www.nrel.gov/docs/fy11osti/46861.pdf)

high as 83° but varies depending on the hour. The high-rise residential thermostat schedule has the same setpoints but no cooling setup and a heating setback temperature of 60°F. The heating setback schedule for high-rise is also slightly different from the low-rise schedule.

Also included in Table 7-2 are the thermostat schedules used by DOE's Building America program and those recommended by DOE for high-rise building modeling. These schedules assume more aggressive heating and cooling setpoints than the Title-24 schedules and are fixed.

Project Team Position on Using Title-24 Thermostat Schedules

The project team ultimately decided against using the Title-24 thermostat schedules for the following reasons:

- Project team feels that both low-rise residential thermostat schedules will result in lower than representative heating and cooling energy use.
- The residential cooling setback was created to adjust cooling energy use by hour to align with statewide demand and not representative of actual cooling setback schedules.

Thermostat Settings from SCE Work Paper and Nest Documents

Based on the data from the two plots on p.30 of the work paper (SCE17HC054, also in Figs. 2 & 3 of the Nest document) and excluding CZ1 (minimal data) and CZ16 (outlier), the mean "comfort setpoint" was 70.3°F for heating and 76.4°F for cooling. These are not far from the 71°F heating and 76°F cooling settings in the NREL House Simulation Protocols or the 70°F heating and 75°F cooling settings in the DOE Commercial Reference Building Models document.

The average setpoints reported in the work paper (66.8°F heating and 75.4°F cooling) and based on RASS are presumably averages across all periods and not representative of what settings would be during occupied and non-sleeping periods. The wide setting ranges in the RASS questionnaire make it difficult to zero in on what setpoints people actually used. The Nest data is more suited to this purpose.

Setback Temperatures and Schedules

If it is assumed that the difference between "comfort setpoint" and "average setpoint" is representative of the measured setback temperature, averaging the "Cooling T-diff" and "Heating T-diff" values across CZ2 to CZ15 from the table on p.42 of the work paper (Table 1 of the Nest document), the mean heating setback was 3.3 and the cooling setup was 2.7. Unfortunately, there is no statistical representation of what times the setting changes occurred. Given the way the Nest operates, temperature changes are based on a combination of occupancy and learned temperature preferences.

The RASS data has too wide a temperature range to be useful for determining scheduled temperatures, but the correction factors on p.35 of the work paper suggest people use somewhat higher heating setbacks than cooling or set-ups. It could be assumed that people set back the temperature in winter during non-occupied periods and/or at night, but summer scheduling is less obvious. Some may set thermostats up while they are at work and crank up the AC when they return. Others may maintain the same temperature during the day and lower it at night to make the house more comfortable for sleeping.

The analysis of RASS data described in the 2004 SCE document, "Programmable Thermostats Installed into Residential Buildings: Predicted Energy Savings Using Occupant Behavior & Simulation" includes the following tables:

Figure 7-1: Table 6 and 8 of 2004 SCE Work Paper

Table 6. Percent of Cooling Systems set to "Off"

	Standard Thermostat				Change due to Prog T-stat			
Region	Morn	Day	Evening	Night	Morn	Day	Evening	Night
NC	49%	28%	13%	56%	-2%	**3%**	**7%**	-2%
SC	63%	43%	42%	65%	-13%	-6%	-16%	-17%
SI	48%	25%	23%	47%	-13%	-5%	-9%	-10%
CV	43%	24%	11%	40%	-10%	-9%	-3%	-3%
DE	37%	14%	10%	35%	-8%	0%	-4%	-10%

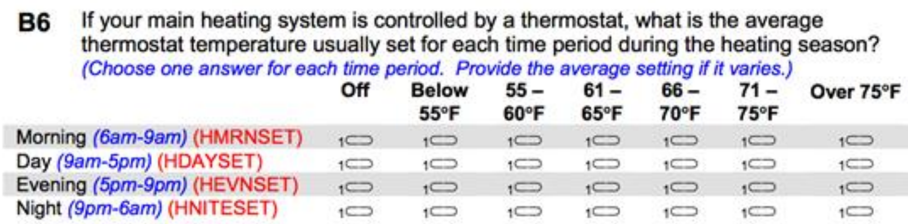
Table 8. Percent of Heating Systems set to "Off"

	Standard Thermostat				Change due to Prog T-stat			
Region	Morn	Day	Evening	Night	Morn	Day	Evening	Night
NC	29%	45%	19%	53%	-12%	-17%	-11%	-13%
SC	40%	57%	35%	54%	-15%	-15%	-16%	-17%
SI	30%	44%	26%	36%	-10%	-12%	-12%	-7%
CV	19%	37%	19%	39%	-10%	-15%	-12%	-10%
DE	27%	34%	23%	35%	-17%	-11%	-14%	-11%

The definitions of time periods are as follows:

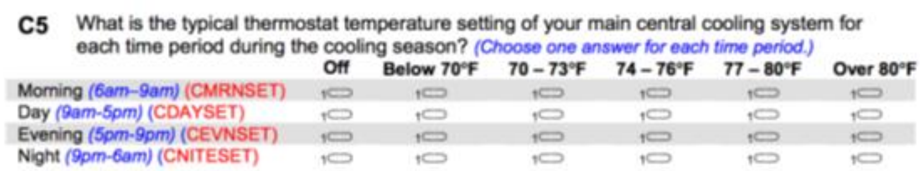
+ Morning: 6 am to 9 am
+ Day: 9 am to 5 pm
+ Evening: 5 pm to 9 pm
+ Night: 9 pm to 6 am

The definition of "off" is based on the RASS questionnaire (below), which includes check boxes for "off" as well as six other temperature ranges. Depending on house temperature response to setbacks and setups, "Off" may yield the same change in indoor temperature and perceived setpoint as certain selected temperature ranges. Respondents may have also used "off" as a proxy for setback/setup.



B6 If your main heating system is controlled by a thermostat, what is the average thermostat temperature usually set for each time period during the heating season? *(Choose one answer for each time period. Provide the average setting if it varies.)*

	Off	Below 55°F	55 – 60°F	61 – 65°F	66 – 70°F	71 – 75°F	Over 75°F
Morning *(6am-9am)* (HMRNSET)	1○	1○	1○	1○	1○	1○	1○
Day *(9am-5pm)* (HDAYSET)	1○	1○	1○	1○	1○	1○	1○
Evening *(5pm-9pm)* (HEVNSET)	1○	1○	1○	1○	1○	1○	1○
Night *(9pm-6am)* (HNITESET)	1○	1○	1○	1○	1○	1○	1○



C5 What is the typical thermostat temperature setting of your main central cooling system for each time period during the cooling season? *(Choose one answer for each time period.)*

	Off	Below 70°F	70 – 73°F	74 – 76°F	77 – 80°F	Over 80°F
Morning *(6am–9am)* (CMRNSET)	1○	1○	1○	1○	1○	1○
Day *(9am-5pm)* (CDAYSET)	1○	1○	1○	1○	1○	1○
Evening *(5pm-9pm)* (CEVNSET)	1○	1○	1○	1○	1○	1○
Night *(9pm-6am)* (CNITESET)	1○	1○	1○	1○	1○	1○

Averaging the percentage across all regions from the tables above, the percentage of time systems are off is:

	6 am-9 am	9 am-5 pm	5 pm-9 pm	9 pm-6 am
Cooling	48%	27%	20%	49%
Heating	29%	43%	24%	43%

Applying a 43% threshold for cooling and heating, most cooling systems would be off at night, and most heating systems would be on in the morning and evening and off at night.

Temperature Ramping

Title 24 standards require that thermostats for heat pumps prevent supplementary heater operation when the heating load can be met by the heat pump alone and require a higher setpoint for heat pump heating than for resistance heating (staged settings). Supplementary (resistance) heating is allowed for defrost and where controls use intelligent recovery or ramping that preclude use of resistance heat. Use of temperature ramps is important for proper characterization of heat pump and strip heat operation.

8 Appendix C: Additional Methods Detail

8.1 Fossil emissions from electricity

8.1.1 DESCRIPTION OF AURORA SCENARIO

Hourly marginal electricity rates are generated by a WECC-wide system scenario in the production simulation tool, AURORA. AURORA takes in system load forecasts, grid characteristics, available generators, technical constraints, and operating costs as inputs to set up system scenarios. Based on those system characteristics, AURORA performs an optimal hourly dispatch of the electric grid to determine hourly wholesale marginal electricity market prices. The developed AURORA scenario includes a detailed forecast of California's electricity system, as well as a broader forecast of the Western Electricity Coordinating Council (WECC) system. Build portfolios and operating characteristics for California's electricity system are determined by E3's RESOLVE capacity expansion model.

In this analysis, the renewable energy build portfolio in AURORA is based on a RESOLVE case that achieves approximately a 74% RPS in 2030. The scenario includes approximately 4 GW of energy storage; this number includes the state mandated targeted 1.3 GW of storage, plus an additional 2.7 GW of economically installed energy storage to accommodate the much higher renewable buildout. Furthermore, the scenario assumes improved regional coordination in the WECC compared to present day operations, as well as high energy efficiency and electrification in transportation and buildings.

8.1.2 MARGINAL EMISSIONS METHODOLOGY

For the 2030 timeframe, this analysis uses short-run marginal emissions to make a conservative estimate of emissions reductions from building electrification. Short-run marginal emissions are the change in grid emissions for a change in demand-side consumption, *without* a change in powerplant capacity. This effectively calculates how the dispatch of existing generators would change based on a change in load. It would be more accurate to use a "long-run" marginal emissions factor, that considers the change in renewable energy capacity to meet new load in accordance with state energy policy. For example, with a goal of 60% RPS in 2030, each additional 1 kWh of new load will require 0.6 kWh of additional renewable energy to be integrated onto the grid, thus reducing the total emissions impact of the new load. Due to the complexity of calculating the time-varying emissions impacts of integrating renewable energy in a high RPS world, a well-established methodology to calculate long-run marginal emissions does not currently exist. Since this analysis uses short-run marginal emissions, the emissions impacts of new electrical load in 2030 will be over-stated, and the total emissions reductions from building electrification will be under-stated.

Hourly short-run marginal emissions are calculated based on hourly forecasted wholesale electricity prices taken from Aurora, using the same methodology that is used in the 2018 CPUC Avoided Cost Calculator[68]. First, forecasted hourly wholesale electricity prices, corresponding forecasted natural gas prices, and assumed variable operations and maintenance costs are used to calculate an implied marginal heat rate. If the implied marginal heat rate is greater than the assumed physical upper bound of existing natural gas power plants, it is then capped at an upper limit; if the implied marginal heat rate is below the lower limit, it is assumed that renewables are the marginal generator, and the heat rate is assumed to be zero. The

[68] http://www.cpuc.ca.gov/General.aspx?id=5267

resulting source energy is multiplied by the distribution losses, and then multiplied by carbon intensity of combusting natural gas to determine the marginal emissions factor.

The marginal emissions rate is reported in metric tons of $CO_{2,\ eq}$/MWh. Figure 8-1 shows the average calculated emissions rate for each month and hour in 2030.

	Hour of Day																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0.33	0.33	0.34	0.33	0.34	0.36	0.39	0.37	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.35	0.33	0.36	0.38	0.37	0.36	0.35	0.34
Feb	0.34	0.34	0.34	0.34	0.34	0.37	0.40	0.30	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.38	0.40	0.40	0.38	0.36	0.35	0.34
Mar	0.27	0.28	0.29	0.28	0.31	0.34	0.25	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.33	0.35	0.35	0.35	0.33	0.32	0.29
Apr	0.18	0.21	0.22	0.20	0.27	0.32	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.17	0.37	0.29	0.28	0.23	0.27	0.25
May	0.26	0.27	0.27	0.27	0.33	0.29	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.25	0.38	0.39	0.35	0.29	0.31	0.28
Jun	0.23	0.24	0.23	0.26	0.30	0.24	0.09	0.01	0.01	0.02	0.01	0.00	0.00	0.01	0.05	0.08	0.08	0.19	0.29	0.37	0.29	0.27	0.29	0.26
Jul	0.34	0.34	0.34	0.34	0.35	0.36	0.33	0.12	0.07	0.10	0.12	0.09	0.05	0.03	0.02	0.02	0.20	0.32	0.36	0.37	0.36	0.36	0.35	0.34
Aug	0.35	0.35	0.36	0.35	0.37	0.39	0.35	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.36	0.39	0.34	0.38	0.39	0.37	0.36	0.36
Sep	0.38	0.37	0.37	0.36	0.38	0.41	0.37	0.21	0.02	0.04	0.00	0.00	0.00	0.00	0.02	0.16	0.36	0.39	0.40	0.39	0.41	0.39	0.37	0.37
Oct	0.35	0.35	0.35	0.35	0.36	0.40	0.42	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.39	0.45	0.43	0.42	0.39	0.37	0.36	0.36
Nov	0.33	0.33	0.33	0.34	0.35	0.36	0.37	0.29	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.35	0.36	0.36	0.36	0.36	0.35	0.34	0.33
Dec	0.33	0.34	0.35	0.34	0.35	0.37	0.40	0.37	0.17	0.00	0.00	0.00	0.00	0.00	0.02	0.12	0.36	0.38	0.39	0.38	0.36	0.35	0.34	0.34

Figure 8-1 Heat map of the assumed marginal emissions rate (metric tons of $CO_{2,\ eq}$/MWh), averaged by month and hour in 2030.

8.2 Methodology for methane and refrigerant leakage calculations

+ Methane leakage was calculated by multiplying the natural gas consumption by 2.8%, the most recent estimate for well-to-burner leakage from scientific literature, and then converted to tonnes of carbon dioxide equivalent emissions (CO_2eq), using the 100-year mass-based global warming potential for methane of 25.[69]

[69] This is based on the IPCC (2007) as used in the CARB inventory. Some recent studies have suggested slightly higher values.

- Refrigerant leakage for AC and heat pump units was calculated using CARB's data on the average charge and leakage rate of refrigerants for residential equipment in California[70]. The total annual leakage rate was obtained by adding the annual operational leakage rate to the annualized end-of-life leakage rate. This annualized rate was obtained by dividing the end-of-life leakage by 18 years, the estimated lifetime of residential HVAC units we use in our study. The resulting annual leakage in lbs of F-gas was converted to tons of CO_2eq emissions using the global warming potential of the refrigerant in each scenario. Additionally, the F-gas charge for each climate zone was assumed to scale linearly with the tonnage of the HVAC system. The F-gas charge data given by CARB was assumed to be for a 4-ton system. Below is an example calculation for the F-gas leakage from the HVAC heat pump for an all-electric, 1978-vintage single family home in Oakland, using the next generation of refrigerants:

$$\text{Annual leakage (tons } CO_{2eq}) = \text{System charge for 4 ton system (lbs)} * (\text{Annual \% leakage} + \frac{\text{End-of-life \% leakage}}{\text{18 years}})$$

$$* \frac{3}{4} \text{ tonnage conversion} * \frac{\text{1 metric ton}}{\text{2204.62 lbs}} * \frac{\text{675 tons } CO_{2eq}}{\text{1 ton R32}}$$

[70] Data obtained through communications with CARB staff.

9 Appendix D: Market Adoption Barriers and Potential Solutions

	Market Participant	Barrier	Potential Solutions	Responsible Entity for Solutions
Both retrofits & new construction	Contractors	Contractors may have limited experience and comfort with electric options	Contractor training, best practices guides, trusted contractor lists	NGOs, CEC
			Utility direct install programs	Load serving entities (LSEs, e.g. utilities and CCAs)
			Upstream incentives	Regulators, LSEs
	Homeowners & Landlords	Limited consumer awareness (and negative preconceptions) of high-efficiency electric technologies	Market education campaign (Energy Upgrade California), new tools for understanding lifecycle savings	NGOs, CEC, LSE outreach
		Low-income consumers have limited access to low-cost financing	Third-party ownership & financing, on-bill financing, PAYS model	Regulators, LSEs
		Consumer unwillingness to pay higher upfront costs; bounded rationality	Downstream direct-to-consumer incentives	Regulators, LSEs

	Market Participant	Barrier	Potential Solutions	Responsible Entity for Solutions
Both retrofits & new construction	Landlords	If renters pay utility bill, landlord does not benefit from bill savings	Incentives for landlords to install high efficiency equipment	Regulators, LSEs
	Homeowners & Renters	Tiered rates discourage electrification	Shift away from tiered rates; avoid collection of fixed costs through volumetric rates; develop rates that more accurately reflect marginal cost to the grid	CPUC, LSEs
	Manufacturers	High costs of product introduction into US market	Increasing market demand, reduce barriers to introduce products that are available internationally	Policymakers
		Limited market demand in US leads to limited production for US market; premium product pricing	Increasing market demand	Policymakers, LSEs
	Utilities	Limited regulatory support for utility programs encouraging fuel switching	GHG performance standard EE programs (i.e. CEOPT pilot for SCE); new cost-test mechanisms	Regulators

	Market Participant	Barrier	Potential Solutions	Responsible Entity for Solutions
New construction	Builders	Builder does not pay full gas infrastructure costs; costs are shared among gas ratepayers	Assess whether new construction should bear a higher cost of gas infrastructure costs	Regulators
		Builders look for least cost, commonly used technologies	Upstream incentives	Policymakers
			Title 24 building code	CEC
Retrofits	Homeowners & Landlords	"Hassle factor" of electrification retrofits & "emergency" replacement of failed equipment may not work with longer-lead time for retrofit installation	Incentives to replace water heater, AC or furnace early when another end-use fails	Regulators, LSEs
			Contractor training to reduce delays	Contractors
			"Electrification-ready" building code	CEC
			Clear identification and communication of market needs to manufacturers, with commitment to purchase or subsidize an initial market segment	Policymakers, NGOs

	Market Participant	Barrier	Potential Solutions	Responsible Entity for Solutions
Retrofits	Homeowners & Landlords	"Hassle factor" of electrification retrofits & "emergency" replacement of failed equipment may not work with longer-lead time for retrofit installation	x-prize type competition for heat pump solutions that bring down the "soft costs" of installation	Policymakers, NGOs
			Design a "plug-and-play" retrofit ready HPWH, heat pump HVAC, and 3-function heat pump	Manufacturers
		Higher upfront costs of heat pump equipment	Improved financing; lease-to-own options, third-party ownership and financing/energy services business model	Private sector, NGOs
	Contractors & distributors	Contractors' existing supply chain focuses on gas technologies; limited stock availability to support emergency replacements	Direct install programs; upstream incentives to encourage replacement readiness; higher market demand	Policymakers, LSEs, NGOs, private sector

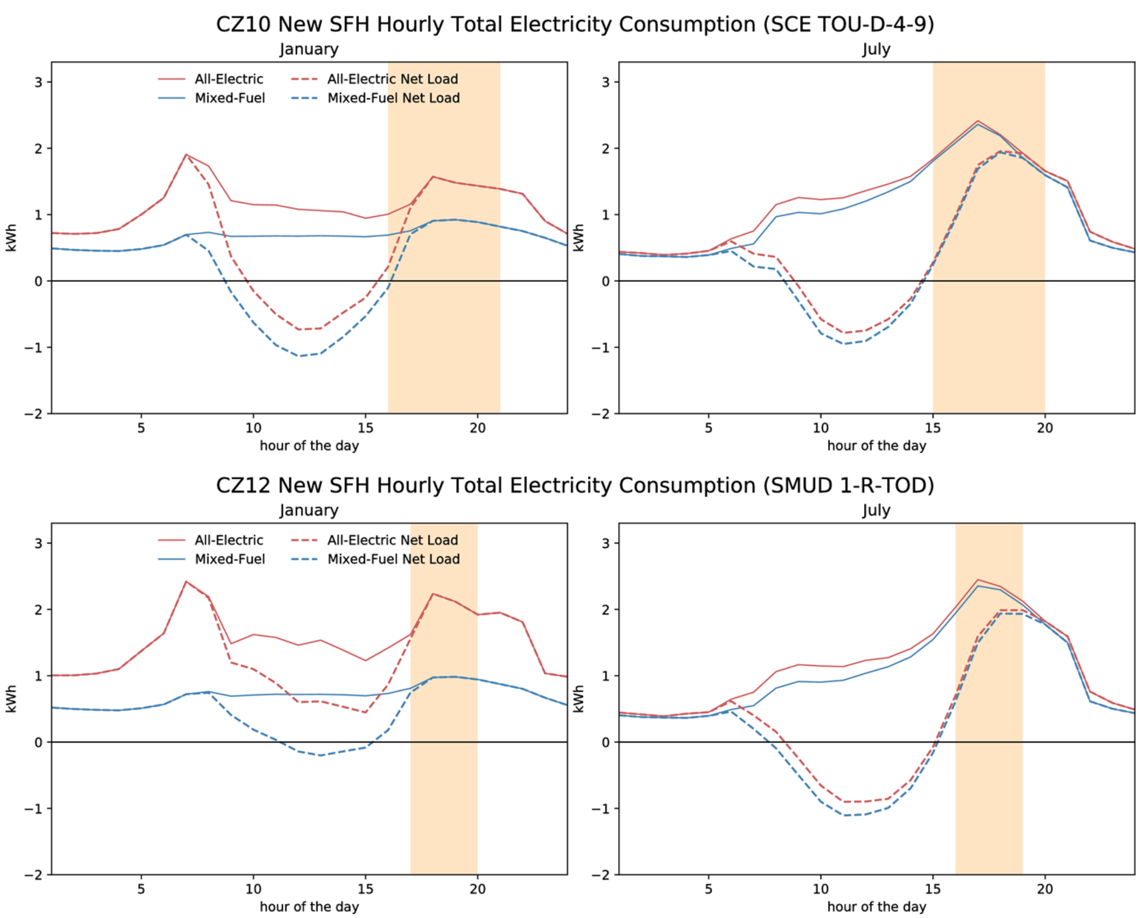
Retrofits, HVAC	Homeowners & Landlords	Offset appliance replacement schedule between heating and cooling appliances	Incentive: Buy-down of remaining useful life of other appliance	Regulators, LSEs
	Contractors	Contractors have limited incentive to sell single HVAC solution instead of two	Upstream incentives; direct install programs	Regulators, LSEs
			Building code requirement for new AC installs to be heat pumps	CEC

	Market Participant	Barrier	Potential Solutions	Responsible Entity for Solutions
Retrofits, DHW	Homeowners & Landlords	Noise and placement concerns when WH is in home	Split-system HPWH products with remote evaporator	Manufacturers
	Contractors	Replacement of gas-fired water heater w/ HPWH requires running 240V power, condensate drain and possible electric panel upgrade	Develop and install products with 120V/15A capability Upstream or midstream incentives; direct install programs	Manufacturers, Regulators, LSEs
		Adequate ventilation not available when existing WH is in interior or exterior closet	Install product with ducted vent kit	Manufacturers, Contractors
Induction stoves	Homeowners & Renters	Consumer preference for natural gas stovetops	Market education campaign about induction stoves; upstream or midstream incentives	NGOs, CEC, LSEs
Clothes dryers	Homeowners & Renters	Heat pump dryers require careful maintenance and can take a long time to dry clothes	R&D in alternative electric clothes dryer solutions (e.g. condensing dryers and microwave/sonic dryers). "X-prize" type competition for a better, high efficiency electric dryer	Manufacturers, NGOs, Policymakers

10 Appendix E: Additional Results

10.1 Electricity load shapes for individual homes simulated

Figure 10-1 Hourly electricity consumption of a new construction single family home in Riverside (CZ10) and Sacramento (CZ12)



Red lines represent the load of an all-electric home; and blue lines show the load of a mixed-fuel home. The net load, represented by the dotted lines, is the total load less the hourly PV generation.

10.2 Site energy savings

Energy savings of up to 73% in residential buildings can be achieved by switching from natural gas to electric home appliances, as building simulation results in this study show (Table 10-1). In single family homes, electric air source heat pumps (ASHPs) achieve higher annual site energy savings than the other home appliances. Low-rise multifamily homes feature much lower annual site energy savings from switching to ASHPs due to the smaller space per home. Space heating demand has a significant influence on annual site energy savings by ASHPs. Colder climates result in about two times larger annual energy savings in Northern California (San Francisco, San Jose and Sacramento) than in Southern California (Los Angeles and Riverside). Retrofit homes achieve higher energy savings using ASHPs because they are less insulated and thus have higher space heating and cooling demand than new construction.

Heat pump water heaters (HPWHs) are the biggest contributor to energy savings in multi-family homes. Compared to space heating and cooling, water heating demand depends more on the number of residents than on the area of the home. Our results show similar site energy savings from switching to HPWHs across home types and vintages. Energy savings achieved by an electric appliance is evaluated by comparing it to the energy consumption of an alternative gas appliance. Benchmarking with a higher-efficiency gas alternative would lower the energy savings achieved by the same electric appliance. New construction homes are more likely to consider newer models of home appliances with higher efficiencies, as compared with retrofit homes. In this study, gas tankless water heaters (81% average efficiency) are chosen for mixed-fuel new construction homes (single family and low-rise multifamily) vs. lower-efficiency gas storage water heaters (63% average efficiency) for retrofit homes. As a result, HPWHs in new construction homes show about half of the energy savings achieved in retrofit homes.

Table 10-1 Annual site energy savings (%) from electrifying a home appliance or an entire home of new construction

	Single Family	Low-rise Multifamily
All-electric Home	70-73%	61-64%
HVAC	32-49%	14-27%
Water Heating	15-24%	27-36%
Clothes Drying	4-7%	2-3%
Cooking	5-7%	7-9%

Electrifying cooking and clothes drying, even with induction stoves and heat pump clothes dryers in single family homes, shows lower annual site energy savings, because there is not as great of an efficiency advantage with these products as compared to shifting from gas water heaters and furnaces to heat pump technology. Prioritizing the electrification of space heating and water heating could achieve 90% of the energy savings benefit of an all-electric home.

Significant energy savings are achieved through electrification of end uses across all building types, vintages and climate zones. Electrifying all end uses in new construction reduces the annual site energy consumption by 30-50% (Table 10-2). The energy savings is much higher in winter than summer. This is because ASHPs are 4 to 6 times more efficient than gas furnaces in providing space heating in California's climate, while efficiency gains in space cooling compared to common AC units are only about 10%. Energy savings in winter for an entire home can be up to 60%, but an all-electric home may achieve much higher savings on days with spiking space heating demand thanks to ASHPs (Figure 10-2). The energy savings may be less significant in colder climate zones if very cold temperatures occur and electric resistance heating needs to be triggered, but electric resistance back-up heat was never triggered in the climate zones and appliances simulated here. Higher space heating demand by retrofit homes contributes to higher site energy savings in all-electric retrofit homes (up to 65%) than in new construction (Table 10-2).

Table 10-2 Site energy savings (%) for new construction, all electric vs. mixed fuel home.

	Single Family	Low-rise Multifamily
Annual	36-50%	34-42%
Summer	25-29%	28-33%
Winter	48-63%	38-51%

Figure 10-2 Daily site energy consumption of all-electric and mixed fuel new construction single family homes