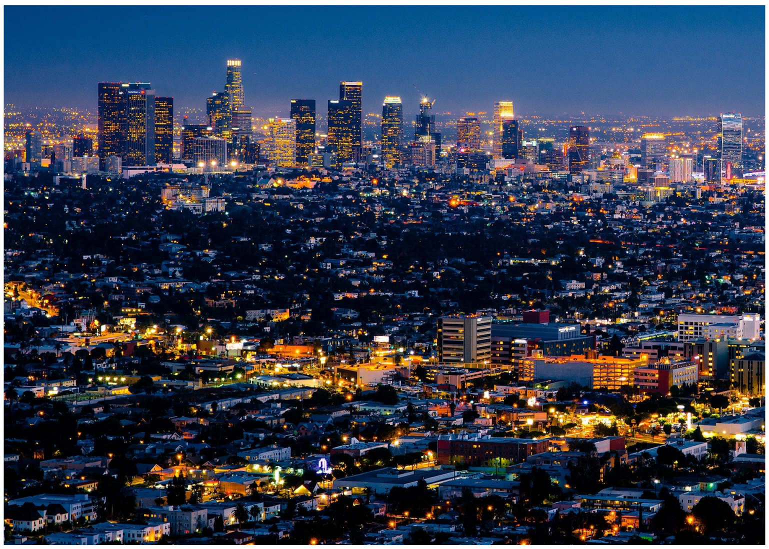
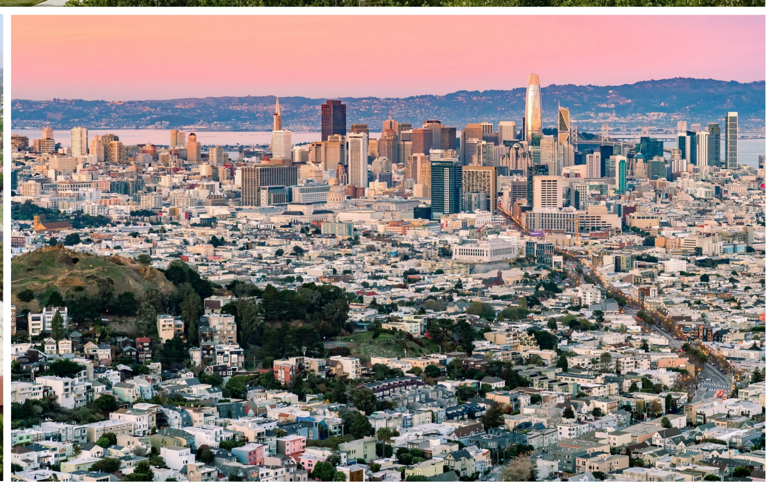
Decarbonization of Heating Energy Use in California Buildings

Technology, Markets, Impacts, and Policy Solutions



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Executive Summary

California has some of the most comprehensive and ambitious clean energy policies in the world, with a recently passed law requiring 100-percent carbon-free electricity by 2045,[1] and an executive order aiming for economy-wide carbon neutrality by the same date. Using strong policies to encourage energy efficiency, renewable energy and clean transportation, the state is making rapid progress toward its goals. But to hit the mark, California will need to turn its attention to an overlooked corner of the emissions picture: the fossil fuels widely used to heat the buildings where Californians live and work.

California's buildings are responsible for 25 percent of the state's climate emissions,[2] and more than half of those emissions come from burning gas or propane in furnaces and water heaters.[3] In fact, nearly 90 percent of California homes use gas for heat or hot water or both. And as the electric grid gets cleaner over time, the share of building emissions from onsite fossil fuel use will only increase, making heating and hot water the lion's share of emissions from energy use in buildings.

Shifting toward clean electric heat in California's homes and businesses will be key to the state's efforts to reduce carbon and air pollution. Today's highly efficient electric heating technologies can provide a cost-effective way to reduce pollution from California's buildings sector, especially as the electric grid continues to become cleaner, buildings become more efficient, and utilities align their pricing with carbon-cutting goals.

Today's Clean, Efficient Electric Heating Technology

Electric heat pumps move heat instead of burning fuel to create heat, making them vastly more efficient than gas-powered furnaces, boilers, hot water heaters, and dryers. Air-source heat pumps for space heating are available today for all of California's climates and building needs, and are already broadly adopted in commercial buildings, particularly in Southern California. Heat pump water heaters can meet the hot water needs for most homes and businesses. Ground-source heat pumps have higher upfront costs, but can also be cost-effective particularly in large buildings and cold climates. Solar hot water with electric backup offers another clean energy solution and can be particularly cost-effective for larger buildings that use a lot of hot water, such as hotels and hospitals. Heat pump dryers provide a low-carbon option for replacing gas or conventional electric dryers, and induction cooktops offer a faster, safer, cleaner alternative to gas cookstoves. However, these technologies today represent a small share of California's market, due to regulatory barriers and higher upfront costs in older homes.

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[1] SB 100 (De Leon), signed by Governor Jerry Brown in September 2018

[2] Brook, M. California Energy Commission. "Building Decarbonization." June 14, 2018 IEPR Workshop on Achieving Zero Emission Buildings.

[3] https://www.nrdc.org/experts/joe-vukovich/real-climate-impact-californias-buildings

Switching to electric heat and hot water will have a significant impact on reducing gas use in California buildings. If a third of California's buildings switched to clean electric heating technology by 2030, emissions from these end uses would fall by **7 million metric tons per year**. That's the equivalent of zeroing out emissions from **1.5 million cars annually or avoiding the climate pollution from nearly four 500-megawatt gas power plants running around the clock**. As California's electric grid continues to shift toward clean, renewable energy sources, emissions from electric heat will continue to drop.

Electric heat and hot water will also save consumers in energy costs over the life of the equipment, particularly if the new systems are used alongside improvements in energy efficiency and utility policies that help customers take advantage of off-peak pricing.

Financial, Comfort, and Health Benefits for Consumers

In new homes equipped with cost-effective solar panels, in line with California's new building code, highly efficient electric heat will cut energy bills by several hundred dollars annually. In older homes without solar, electric heating would be cost-competitive with gas when combined with simple energy efficiency improvements, such as attic insulation and air sealing. Savings vary depending on climate, building type, and especially utility rates. Electric rates with a significant difference in peak and off-peak pricing offer opportunities for customers to set their heat pumps to operate when electricity is cheapest and cleanest.

Upfront costs of clean electric heating are generally lower than conventional gas alternatives in new construction, by $1,500 or more in our model, as higher heat pump equipment costs are more than offset by avoiding the cost of plumbing the building for gas and connecting it to the gas main in the street, as well as by using a single heat pump for heating and cooling instead of a separate furnace and air conditioner. Operational energy costs vary by rate design, climate zone, and by how much solar is on the building. By sizing the solar array to generate enough electricity to power clean electric heating in addition to conventional electric loads like cooling, lighting, and plug-in equipment, home owners can save between $200 and $500 annually on their utility bills. From a lifecycle cost perspective, clean heating in new buildings can range between savings of more than $8,400 to a small net cost of under $400. Across climate zones, higher cost savings are achieved by using more dynamic electric rates and by maximizing cost-effective solar PV to supply the larger electric load.

In existing buildings, upfront costs of clean heating retrofits are generally higher and they vary more from home to home. For example, from $1,500 in *lower* costs when replacing both the furnace and air conditioner with a heat pump along with minimal electric upgrades, to $900 in *higher* costs when replacing only the furnace. Electrical wiring, panel and/or service upgrade may be required in some homes, whether for heat pumps, electrical vehicle chargers, or just safety upgrades. When required, electrical upgrades could range from another few hundred dollars for wiring only to several thousand for a panel and/or service upgrade.

Operational energy costs in existing buildings also vary, depending on rates and location, but customers can reduce energy bills by up to $500 to $800 in the Bay Area and Sacramento where heating demand is higher than in the Los Angeles region, when using electrification-friendly rates, some basic air sealing and attic insulation energy efficiency upgrades, and on-site solar. The lifecycle cost of clean heating retrofits in existing buildings varies between savings of $7,300 and an extra cost of $9,700, showing the need for market development to bring down the cost of the technology and make it accessible to all. Life cycle cost-effectiveness is increased when pairing electrification with energy efficiency and more dynamic rate designs and by maximizing cost-effective solar PV to supply the larger electric load.

Using clean electricity instead of gas heat will reduce greenhouse gas emissions by between 31 percent and 73 percent depending on the size of the solar array and climate zone. These reductions come from the much higher energy efficiency of heat pump technology compared to gas alternatives, combined with powering them with cleaner electricity.

Clean heating can also improve health, safety, and comfort. Electric heating technologies improve indoor air quality by avoiding indoor combustion emissions that can cause headaches, fatigue, queasiness, eye, nose, and throat irritation, and serious lung disease, including cancer and other health impacts.[4] Heat pumps can also increase home comfort by operating virtually silently and providing more stable temperatures.

Electric Grid Benefits

Without additional energy efficiency measures, we find that the widespread use of electric heat could increase California's overall electricity use by approximately 19 percent, while decreasing gas use by a third. But done right, with energy efficiency and if much of the additional load is shifted to off-peak hours when renewable energy is plentiful, electrification can reduce electric system costs. The smart use of electric heat would spread fixed grid infrastructure costs over higher electricity sales and would help absorb surplus renewable energy during periods of low demand, helping achieve California's goal of a 100-percent carbon-free grid in an affordable manner.

Electric water heaters and, to some extent, reasonably well-insulated and airtight buildings can act like thermal batteries, storing heat for later use. By pre-heating hot water tanks and buildings during times when demand is low or when renewable energy is abundant, homes and businesses can shift more of their electricity use to off-peak hours. This would reduce peak strain on the grid and also help integrate more renewable energy into the system.

Buildings that can use electric heat to store clean, renewable energy instead of burning gas on site would be assets on a renewable grid. Efficient heat pumps, paired with building efficiency measures such as insulation and smart thermostats, will be key to cost-effective emissions cuts.

[4] California Air Resources Board, https://www.arb.ca.gov/research/indoor/combustion.htm

Policy Recommendations

Most buildings are around for 50 to 100 years or more, and the space and water heating equipment within them lasts 10 to 20 years. To take advantage of natural equipment replacement cycles, high-efficiency electric heat pumps need to become mainstream by 2030.

This gives California a dozen years to develop the market and make this heating technology affordable and accessible to all. The technology exists, it needs policy support to jump start its sales, reduce its costs, and make it more broadly available. Specific policy changes can help make this happen:

- **Raise awareness and educate** customers, policy makers, product distributors, and the building trades on the technology's availability, and its financial, health, safety, and comfort benefits. Lack of awareness is one of the key barriers to adoption of this emerging clean energy technology.

- **Set targets and develop plans** to create market certainty, encourage investment, and provide a clear framework to guide the development of new policies and programs (and secure stable funding for those programs).

- **Remove regulatory and market barriers** that are hindering market development, by updating policies such as incentive programs, limitations on fuel-switching programs, and rate design, to reflect California's clean energy resources and policy objectives. Also remove accessibility barriers through financial incentives and financing to overcome capital cost and product availability issues.

- **Transform the market** by accelerating and scaling adoption through mechanisms such as building codes, integrating electrification with other policies such as energy efficiency retrofits, and continued product research, development, and deployment programs.

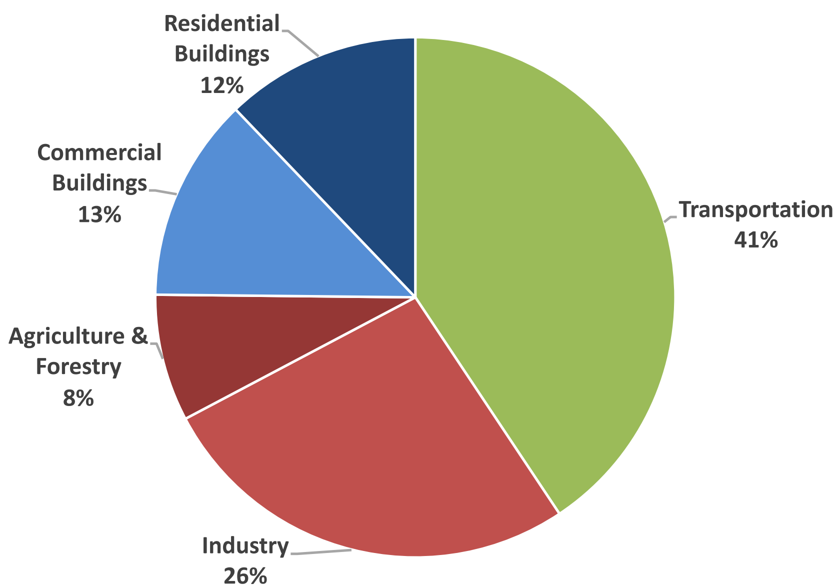
Done right, building decarbonization will also provide major affordability, quality of life, and public health benefits to Californians. But reaping these benefits requires massive market transformation, on the scale of the renewable electricity and electric vehicle revolutions. The decarbonization of California's buildings will take decades, but it must start now to avoid unnecessary stranded costs and set in motion the virtuous cycle of declining equipment, installation, and operating costs that will make clean and affordable buildings accessible to all.

California can also have an outsized influence on the rest of the world, which is looking at the Golden State for clean energy leadership. Addressing California's building decarbonization challenge in a way that benefits customers, the grid, and the environment is critical to achieving our climate and clean energy goals globally.

1. INTRODUCTION

California has set ambitious goals for reducing greenhouse gas (GHG) emissions: 40 percent below 1990 levels by 2030, and 80 percent by 2050. Emissions today are close to 1990 levels; returning to those levels is the state's target for 2020. Emission reductions to meet the 2020 target have come primarily from transportation (due mostly to increasing fuel economy) and electric power (where renewable energy has risen to more than one third of the state's portfolio[5]). However, the deep decarbonization needed to hit the remaining targets will require progress across all sectors. Transportation, industry, and agriculture will be the hardest sectors to decarbonize by 2050,[6] so the buildings sector must exceed 80 percent reductions in order to meet the state's goal.

Figure 1. 2016 California GHG emissions by sector. Electric sector emissions are assigned to the end use sectors that consume electricity.



Source: California Air Resources Board. "2018 Edition California Greenhouse Gas Inventory for 2000-2065 — by Sector and Activity" Accessed Sept. 4, 2018 at https://www.arb.ca.gov/cc/inventory/data/tables/ghg_inventory_by_sector_sum_00-16.xlsx. U.S. Energy Information Administration State Energy Data System used to apportion electric emissions.

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[5] California Public Utilities Commission, *Renewables Portfolio Standard Annual Report*, November 2017. http://www.cpuc.ca.gov/uploadedFiles/CPUC_Website/Content/Utilities_and_Industries/Energy/Reports_and_White_Papers/Nov%202017%20-%20RPS%20Annual%20Report.pdf.

[6] Subin, Z., Energy + Environmental Economics. "Long-Term Energy Scenarios In California: Implications for Building Decarbonization." June 14, 2018 IEPR Workshop on Achieving Zero Emission Buildings.

The transportation sector is the largest greenhouse gas emitter in California, while residential and commercial buildings (25 percent combined) follow just behind industry. This report addresses the options for, and impacts of, decarbonizing California's buildings. Emissions from electricity consumption in buildings will fall as the state's electric supply portfolio decarbonizes, but other strategies and technologies will be required to address the emissions from combustion of fuels for space and water heating, along with other incidental uses like cooking, in buildings.

California cannot reach deep decarbonization in the most cost-effective manner without switching a large share of its buildings from fossil fuels to high-efficiency electric heating appliances powered by low-carbon electricity. Between 2000 and 2016, emissions from fuel combustion in California's residential buildings fell 18 percent, while combustion emissions in commercial buildings rose 9 percent.[7] In total across all buildings, combustion emissions fell 10 percent over 16 years, largely due to efficiency gains. This is encouraging but falls short of the pace needed to decarbonize the building sector in line with the state's climate goals.

The technologies we analyze in this report have the potential to accelerate that pace of reduction, adding to the reductions expected from continued energy efficiency. If 30 percent of residential and commercial buildings adopted electric heat pump or other non-combustion technology for space and water heating by 2030, consumption of natural gas in buildings would fall by 174 billion cubic feet per year, while annual electric consumption would grow by 17 million MWh. Since 60 percent of those added MWh will be renewable by 2030, thanks to California's renewables portfolio standard, emissions from these end uses would fall by **7 million metric tons per year**, or 18 percent of 2016 building fuel combustion emissions. This is the equivalent of taking **1.5 million cars off the road each year** or avoiding the emissions from a **nearly four 500 MW natural gas power plants running around the clock**. The emissions reductions continue to rise as the renewable and other zero-carbon portion of the electric sector increases, reaching 100 percent in 2045 per the state's recently signed SB 100 law.

This report focuses on electrification as one of the major pathways for building decarbonization because it has received less attention in the state's climate policies to date, and has only recently emerged as a priority with laws AB 3232 and SB 1477 signed by the Governor in 2018. Cost-effectively decarbonizing buildings with electrification requires parallel progress in three additional areas: energy efficiency, load management, and reducing the carbon intensity of electric generation. As discussed above, California is making substantial progress on electric generation. The state has active programs and policies for energy efficiency. Policymakers and the industry are also actively working to increase the potential for dynamic loads, electric vehicles, and energy storage to increase the responsiveness of end use demand to grid conditions. Throughout this report we identify places where electrification complements or requires progress in these other areas.

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[7] California Air Resources Board, "California Greenhouse Gas Emission Inventory - 2018 Edition, Economic Sector Characterization," accessed Sept. 4, 2018 at https://www.arb.ca.gov/cc/inventory/data/tables/ghg_inventory_by_sector_all_00-16.xlsx.

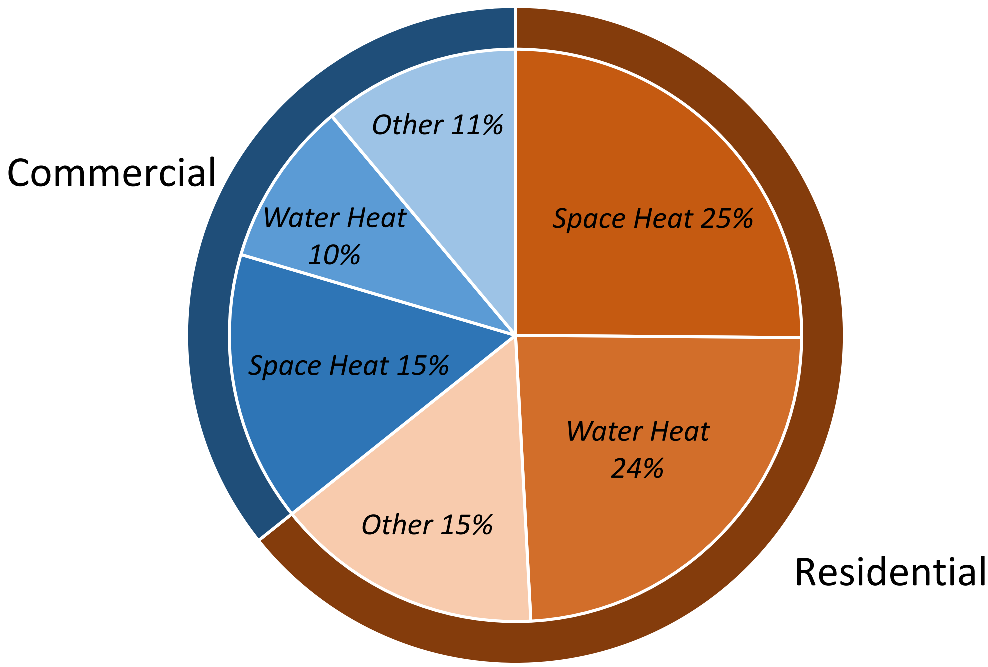
Why focus on electrification for buildings instead of low-carbon fuels?

Renewable gas produced from decay of wastes in sources like landfills or digesters, and other bio-energy and synthetic options for zero- or low-emission combustible fuels, are important parts of a cost-effective solution to California's climate challenges. Their contribution comes in part through the need to capture methane from biogenic sources such as dairies and landfills. However, their limited availability and high cost limit them to be a piece of the solution, not a wholesale alternative to large-scale electrification of the building sector. In addition, limited supplies of renewable gas should be directed first to those end uses where electrification is not a technically or economically viable option.

As supplies allow, biogas and liquid fuels would also supply other areas where the particular qualities of a combustible and energy-dense hydrocarbon fuels provide an advantage: long-haul transportation and off-road transportation (including aviation and water-borne shipping) as well as combined heat and power (CHP) and other industrial processes. The federal plan showing the nation's path to emission reductions beyond the Paris Agreement identifies somewhat more than 6 quadrillion BTUs (quads) of bioenergy across the U.S. economy by 2050, of which less than 0.4 quads would be used in the buildings sector. To provide a sense of scale, California buildings alone today use about 0.7 quads per year from on-site combustion of fossil fuels.

On-site fuel combustion in buildings primarily serves two purposes: space heating and water heating. Together, these two uses are responsible for more than 80 percent of direct fuel use in residential buildings and about 70 percent in commercial buildings. (Figure 2 shows the division of building demand by use and subsector.) The remainder primarily serves cooking and clothes drying demand. Today's technologies can electrify all of these end uses, and these technologies are used in both efficient and fully electric new buildings being constructed today. Solar heating—whether via passive solar design or direct capture for water heating—can also contribute. Sections 2, 3, and 4 address the technology options and markets for space heating, water heating, and other uses, respectively.

Figure 2. California's 707 trillion BTUs of on-site fuel consumption in buildings in 2016, divided by end use and sub-sector



Source: California Air Resources Board 2018 GHG Inventory; U.S. Energy Information Administration, 2009 Residential Energy Consumption Survey and 2012 Commercial Buildings Energy Consumption Survey

In order to move markets for high-efficiency electric heating technologies, customers must demand the new products offered. Natural gas has come to dominate residential and commercial building on-site combustion because it is relatively inexpensive and provides valued services. Electric options for decarbonized buildings must compete on price as well as on service. Section 5 evaluates the cost side of this challenge. We do this by estimating the upfront capital costs and ongoing energy costs for both existing and new buildings adopting electric technologies in three different regions of the state.

Electrification of buildings will have impacts on the electric grid and electric utilities, especially when pursued in concert with transportation electrification. Water heating electrification has parallels with vehicle electrification, because the appliance has built-in storage and can be used as a grid resource. Section 6 estimates the extent of grid impacts from building electrification between now and 2030 on the pathway to deep decarbonization and puts them in the broader context of electric system transformation, electric vehicle growth, and renewable electricity supply.

Section 7 identifies California's current programs and policies that impact the pace of deep decarbonization of buildings. We also identify policies from other states that could inform California policymakers, as part of a survey of possible actions that policymakers, regulators, utilities, and other market actors could take to advance the decarbonization of buildings. Section 8 concludes the report.

2. SPACE HEATING

Space heating is the largest driver of fossil fuel use in California buildings. Decarbonizing buildings cost-effectively requires moving to energy efficient heat pumps which use the state's increasingly low-carbon electric supply. While electric resistance heat has been a heating option for many decades, it is inefficient and expensive to operate. Heat pumps can replace resistance heating in many places, reducing electric consumption and customer utility bills.

2.1. Market Opportunity

Residential space heating market

Residential space heating in California accounts for about 26 percent of the total energy use in the residential building sector.[8] Among all fuel sources, natural gas has been the dominant fuel for space heating with about 86 percent usage share, followed by electricity with about 8.5 percent, and propane with about 5.5 percent.[9] About 86 percent of the residential natural gas heating systems are forced-air systems with ducting, according to the 2012 California Lighting and Appliance Saturation Survey (CLASS). Hydronic (radiator) heating distribution systems are very limited in the state.

The 2012 California Lighting and Appliance Saturation Study indicated that just 2 percent of California homes with heating used heat pumps as their primary heat source. Air-source heat pumps (ASHPs) initially became available in the U.S. market after the oil crisis in the 1970s,[10] but the penetration of this technology is still limited except in mild climate zones. In 2015, the penetration rates of heat pumps among households were only 3 percent in the Northeast, 6 percent in the Pacific region, and more than 25 percent in the South Atlantic region (where mild temperatures, near-universal air conditioning, and affordable electricity combine to create favorable customer economics for heat pumps). The national average is 10 percent.[11]

Commercial space heating market

The landscape of heating fuels for commercial buildings is very different from that for residential buildings. The energy usage for space heating accounts for about 18 percent of the total commercial energy use in the Pacific region.[12] While natural gas is still a dominant heating fuel in commercial

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8 RECS 2009. Table CE3.5 Household Site End-Use Consumption in the West Region, Totals and Averages, 2009

9 RECS 2009. Table CE4.5 Household Site End-Use Consumption by Fuel in the West Region, Totals, 2009

10 https://info.ornl.gov/sites/publications/files/Pub46296.pdf.

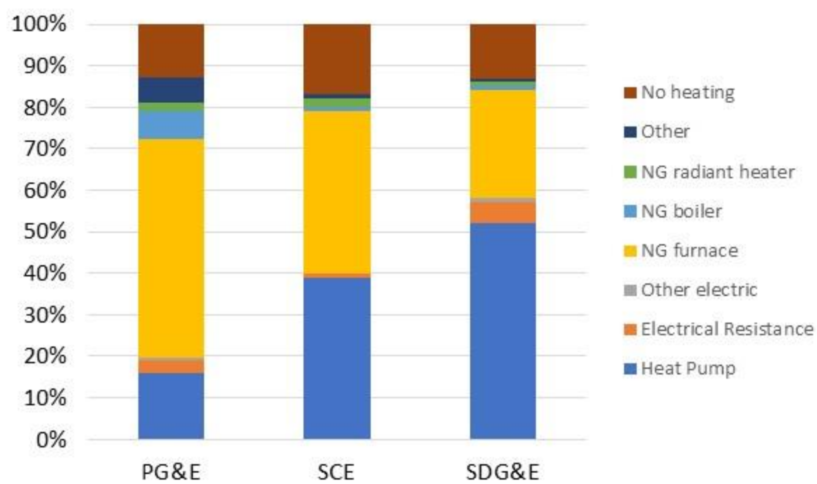
11 EIA Residential Energy Consumption Survey (RECS) 2015, Table HC6.7 and HC6.8, Available at https://www.eia.gov/consumption/residential/data/2015/hc/php/hc6.7.php and https://www.eia.gov/consumption/residential/data/2015/hc/php/hc6.8.php;.

12 Energy Information Administration (2012). Commercial Building Energy Consumption Survey (CBECS). Table E1.

buildings in Northern California ("NG furnace" for "PG&E" as shown in Figure 3), electrically heated buildings are equally dominant to natural gas heating in the Los Angeles area (as shown as "Heat Pump" and "NG furnace" for "SCE" category in Figure 3) and exceed natural gas heated buildings in the San Diego area (as shown as "Heat Pump" for "SDG&E" category in Figure 3).

The share of electric heating systems is generally greater in warmer climate zones, such as in the San Diego area. According to the 2014 California Commercial Saturation Survey (CSS), the share of commercial buildings with electric heating systems is about 20 percent in Northern California, 40 percent in the Los Angeles area, and 57 percent in the San Diego area. The majority of the electric heating systems (from 85 to 98 percent) are ducted heat pump systems (Figure 3).

Figure 3. Commercial heating fuel type and distribution equipment type by utility, weighted by number of buildings



Source: Itron (2014) California Commercial Saturation Survey.

2.2. Technologies: Heat Pumps

An electric heat pump is an energy efficient heating and cooling system that can heat buildings by moving heat from outdoors to indoors (during winter) and cool buildings by moving heat from indoors to outdoors (during summer). Because a heat pump moves heat rather than generating it, the efficiency of heat pumps can be over 100 percent. In fact, heat pumps typically have a high "coefficient of performance" (COP): the ratio of useful heating or cooling to the total energy input. For heating season, heat pumps could typically have a COP exceeding 3, meaning a heat output 300 percent of the energy input. For cooling, heat pumps can have coefficients of performance over 6. A heat pump heats or cools buildings through a vapor-compression refrigerant cycle connecting an outdoor compressor with indoor heat exchanger. For cooling, a heat pump is the same as an air conditioner (moving heat from inside to outside). For space heating, a heat pump reverses the flow of refrigerants and extracts heat from the outside environment—even in cold winter weather—and feeds it into the building.

In addition to efficiency, a key health and safety benefit of heat pumps compared to fossil fuel-based heating is the lack of any indoor combustion emissions, such as carbon monoxide (CO), nitrogen dioxide (NO_2), fine and ultrafine particles, polycyclic aromatic hydrocarbons (PAHs), and formaldehyde. At elevated levels, carbon monoxide causes headaches, fatigue, queasiness, and can even be lethal. Other combustion pollutants can cause eye, nose, and throat irritation, and serious lung disease, including cancer and other health impacts.[13]

Many heat pumps also provide more stable temperatures, increasing comfort, thanks to the use of variable speed compressors. They also provide quiet, continuous heat instead of the loud blasts of hot and cold air provided by many forced air furnaces common in California.

Heat pumps are categorized based on the heat sources they draw from to heat buildings. The different categories of heat pumps are:

- **Air-source heat pump (ASHP):** The most common type in the United States moves heat between indoor-air and outdoor-air. The bulk of this chapter deals with ASHPs due to their dominance in the market. The various configurations of ASHPs are discussed below, after each of the general heat pump categories are described.
- **Ground-source heat pump (GSHP):** Systems that use underground rock or groundwater as the outdoor heat reservoir are generally called GSHPs. GSHPs have an indoor heat pump unit and a heat exchanging ground loop buried underground to transfer heat between the ground and the building. They are generally more efficient than ASHPs as they extract heat from the ground that is relatively warmer than outdoor air. However, they are much more expensive to install due to the drilling requirements and ground loop components.[14]
- **Water-source heat pump (WSHP):** When heat is extracted from a body of water, a heat pump system is called a WSHP. If a building has easy access to a well, lake, aquifer, or other thermal reservoir (e.g., wastewater, cooling loop system), WSHPs could be a viable and less expensive option than a GSHP because WSHPs do not require extensive ground drilling or excavation. Both GSHPs and WSHPs have various system sizes which can be used for buildings ranging from single-story buildings to large, high-rise buildings, and district heating systems where a central heat pump serves multiple buildings.
- **Air-to-water heat pump (AWHP):** An AWHP**,** or "hydronic heat pump", heats interior water instead of air. AWHPs have become broadly available as hot water heat pumps for households in the United States in the past few years (as will be discussed in the next

[13] California Air Resources Board, https://www.arb.ca.gov/research/indoor/combustion.htm

[14] U.S. Department of Energy (DOE). n.d. "Geothermal Heat Pumps" Available at https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems/geothermal-heat-pumps.

section). However, AWHPs for space heating are not widely available for use in the United States and are more expensive.[15]

ASHPs are available in several different forms:

- **Ducted ASHPs**: Ducted ASHPs are split systems where the outdoor unit and indoor fan coils are separated and connected with refrigerant pipes and electric wires. Ducted ASHPs use conventional air ducts to distribute heating and cooling from an indoor unit throughout an entire building. Most popular ducted ASHP models in the United States are a single-speed or two-speed models. However, more efficient variable speed compressor models have recently become available in the U.S. market. Ducted ASHPs can be cold climate systems, but more commonly have electric resistance heating as auxiliary heating support for the coldest days. Commercial applications of ducted ASHPs are often called rooftop units as they are typically installed on the roof.

Figure 4. Ducted ASHPs collect heat with an outdoor unit and then use ducts to transport heat around the building.

Sources: inteGreen Services Inc.[16] and Energy Smart Home Performance[17]

- **Ductless mini-split ASHPs**: Ductless mini-split ASHPs use refrigerant pipes (instead of ducts) to deliver heating or cooling to each room where an indoor unit is installed. Ductless ASHPs—initially developed by Japanese manufacturers and now used extensively in Europe and Asia—have been gaining popularity in recent years in the United States. They have excellent zone controls and no duct-related energy loss, and

[15] Daikin's Altherma heat pump can provide space heating, domestic hot water, and cooling for residential buildings. While it has been several years since this product was introduced in the U.S. market, the adaptation is very limited, likely due to its cost. See http://www.greenbuildingadvisor.com/articles/dept/musings/air-water-heat-pumps.

[16] http://www.integreenservices.com/photo-gallery/2-before/detail/149-trane-heat-pump-hvac-system.html

[17] http://energysmartohio.com/case_studies/1900-net-zero-ready/

they are generally more energy efficient than ducted models. A vast majority of mini-split ASHPs available are variable speed compressors, and there are cold-climate systems available.

Figure 5. Ductless mini-split ASHPs use refrigerant pipes (instead of ducts) to deliver heating or cooling to each room where an indoor unit is installed.

Source: Energy Star[18]

- **Packaged terminal systems**: Packaged terminal air-conditioners (PTAC)/heat pumps (PTHP) are stand-alone systems that contain all components (compressor, condenser and evaporator coils, fans, etc.) in one place, located on an exterior wall. PTHPs are often installed in hotels and apartments. Current mainstream technology does not perform well in cold climates, and thus typically has backup electric resistance heating elements, but variable capacity PTHPs are now also available in the US.[19]

Variable refrigerant flow (VRF) ASHPs: VRF ASHPs are another type of ductless ASHPs with a larger capacity and advanced refrigerant controls.[20] VRFs are suitable for medium-to-large commercial buildings (e.g., big box retails or buildings with four or more stories) while ductless mini-split systems are mainly used for residential and small commercial buildings. VRF systems have been used in Asian countries for many years. The largest penetration is in Japan at 50 percent of small/medium commercial buildings and nearly 30 percent of large size buildings as of 2014.[21] VRF systems were introduced

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[18] https://www.energystar.gov/products/heating_cooling/ductless_heating_cooling

[19] https://www.directsupply.com/resources/selection-guides/PTAC-selection-guide.pdf

[20] Bonneville Power Administration (2016). HVAC Market Intelligence Report

[21] http://www.asiagreenbuildings.com/7809/development-market-penetration-vrf-systems-asia/

in the U.S. market in 2003.[22] While VRF is still an emerging technology in the United States, it experienced rapid growth during the last few years, and it is expected to grow rapidly in the next decade or so.[23] VRF models can distribute heating and cooling to numerous indoor evaporator units (as much as 50) from a single outdoor unit over a single long refrigerant line.[24] When combined with a heat recovery system, VRF systems use sophisticated refrigerant controls to provide heating and cooling simultaneously in different rooms.[25] Further, VRF systems require less space than ducted systems or central heating and cooling plants.[26,27] However, VRFs also present a higher risk of negative climate impacts from refrigerant leakage due to the higher volume of refrigerant they contain and the higher risk of leakage. An accelerated transition to low-global-warming-potential refrigerants will be key to fully realizing the climate benefits of VRFs.

A recent study simulated the performance of a VRF system across the United States. The study compared the VRF performance against a rooftop unit with a variable air volume system that contains a natural gas furnace and a conventional air conditioner. This study found that a VRF system can save heating energy by 50 percent in San Francisco and 56 percent in Los Angeles.[28]

A few manufacturers have also developed new types of VRF systems that could be more applicable to the existing commercial building HVAC environment. One such system is an air-to-water VRF system that can exchange heat between refrigerant and water in a control system located in a building and distribute hot water or cold water to each indoor unit (instead of refrigerant).[29] Another type is a water-source VRF system that combines aspects of water/geothermal heat pumps and VRF systems.[30]

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[22] Mitsubishi Electric (2016). Advanced Heating Technology: Applying VRF in Cold Climates (White Paper).

[23] Bonneville Power Administration (2016). HVAC Market Intelligence Report

[24] Mitsubishi . n.d., City Multi Brochure (CM11WD-I), p. 83, Available at https://www.mitsubishielectric.com.au/assets/LEG/MEE10K026_CM11WD_I_w.pdf

[25] Pacific Northwest National Laboratory. 2012. Variable Refrigerant Flow Systems, prepared for the General Services Administration, Available at https://www.gsa.gov/cdnstatic/GPG_Variable_Refrigerant_Flow_12-2012.pdf

[26] Id. p. 5; https://www.proudgreenbuilding.com/articles/vrf-solution-provides-efficiency-for-luxury-residential-retrofit/

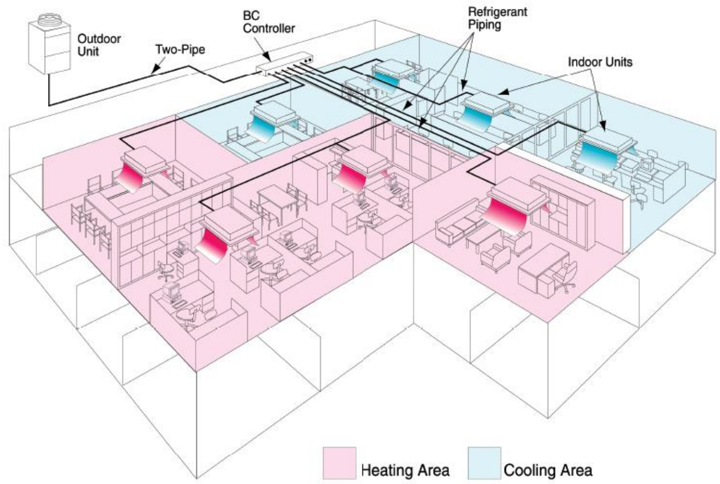
[27] For example, a six-story historical building in downtown Providence, Rhode Island that was recently renovated into a 196 loft-style luxury residences and installed a VRF system to take advantage of various VRF benefits. The VRF's limited space requirements allow the building to repurpose a mechanical room for amenities for the residents including a gym and a theater, and to create a large outdoor space on the roof overlooking downtown Providence for the residents. For more details, see https://www.proudgreenbuilding.com/articles/vrf-solution-provides-efficiency-for-luxury-residential-retrofit/

[28] Dongsu Kim, et al. 2017. Evaluation of Energy Savings Potential of Variable Refrigerant Flow (VRF) from Variable Air Volume (VAV) in the U.S. Climate Locations. Energy Reports Journal, 3 (2017) 85–93.

[29] Mitsubishi calls this system "hybrid VRF", http://www.mitsubishi-electric.co.nz/citymulti/hvrf.aspx.

[30] Mitsubishi Electric. 2014. Best of Both Worlds: Water-source VRF Zoning Systems Combine Benefits of Geothermal and Variable Refrigerant Flow Technology, available at https://www.mitsubishipro.com/pdfs/6-geothermal.pdf; Trane. n.d. Trane Water-Source Variable Refrigerant Flow, available at

Figure 6. Variable refrigerant flow systems can provide simultaneous heating and cooling



Source: Mitsubishi[31]

Although rare in California, some buildings use radiant heating systems. Households and commercial facilities with such heating distribution systems can also install solar hot water heaters (SHWH), heat pump water heaters (HPWH), or reverse cycle chillers. The technological characteristics of these options are discussed in detail in the next section.

District heating

District heating consists of a central plant that generates heat and a network of insulated pipes to distribute it to nearby residential and commercial buildings. These systems are most common in urban core areas with high building density, and on large campuses such as universities, hospitals, and office parks. Conventional district heating systems often use fossil fuels, but large geothermal or water-source heat pumps are increasingly used in those applications, such as with Stanford University's SESI system.[32] District heating heat pumps can absorb low temperature thermal energy from surface water or aquifers, as well as recover and redistribute waste heat from commercial and industrial processes such as data centers and sewage treatment plants.

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https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/equipment/ductless/variable-refrigerant-volume/Water%20Source%20Brochure%20VRF-SLB012-EN.pdf

[31] https://access-inc.com/wp-content/uploads/sites/8/2015/08/mitsubishi_VFR_HVAC.jpg

[32] http://sustainable.stanford.edu/campus-action/stanford-energy-system-innovations-sesi

Cold climate heat pumps

Conventional heat pumps that rely on a simple vapor-compression cycle do not perform well under freezing temperatures and thus need electric resistance heating as a back-up heat. This adds a significant operational cost for homeowners and businesses, and could stress the electric grid at scale, especially in cold climates. New heat pumps called cold climate air-source heat pumps, or ccASHPs, were introduced recently in the U.S. market and are gaining popularity among households and businesses because they have superior performance under freezing temperatures. These heat pumps can be installed anywhere in California without use of resistance heat backup. This means they remain more efficient than resistance systems, and do not draw as much power from the grid, even at the coldest times. As a result, they have the potential to provide winter comfort without triggering the need for an electrical panel upgrade, and produce smaller winter peak grid impacts.

Cold climate heat pumps have variable-speed compressors which allow the systems to operate more smoothly and efficiently by varying capacity with building loads.[33] This also allows the systems to operate efficiently in cold climates. Northeast Energy Efficiency Partnerships (NEEP) has developed a *Cold Climate Air Source Heat Pump Specification*, which requires heat pump products to have at least 1.75 COP at 5 °F to be listed as a cold climate product. NEEP developed, and has been maintaining, a list of products that meet that specification with help from manufacturers.[34] As of February 2018, the list has nearly 850 ccASHP products.

Field studies conducted over the past few years have proven the high efficiency of ccASHPs. For example, one recent study evaluated ccASHPs and confirmed their high performance in the coldest temperatures in Vermont. The study found that the average performance of heat pumps was about 1.6 COP at 5 °F, and above 1 even under -20°F, suggesting the systems were more efficient than electric resistance heating systems even at the coldest temperatures.[35] These study results clearly show that ccASHPs can operate efficiently in many cold climate zones without electric resistance heating systems including certainly any parts of California.

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[33] NEEP (2017). Northeast/Mid-Atlantic Air-Source Heat Pump Market Strategies Report 2016 Update, January 2017.; U.S. DOE. (2015). Building America Case Study – Field Performance of Inverter-Drive Heat Pumps in Cold Climates, https://www.energy.gov/sites/prod/files/2015/09/f26/ba-case-study-inverter-driven-heat-pumps-cold.pdf

[34] NEEP Cold Climate Air Source Heat Pump Specification, http://www.neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump

[35] Design temperature levels in California climate zones range from 15 to 44. See "The Pacific Energy Center's Guide to: California Climate Zones and Bioclimatic Design" accessible at https://www.pge.com/includes/docs/pdfs/about/edusafety/training/pec/toolbox/arch/climate/california_climate_zones_01-16.pdf.

Refrigerant leaks: Should they be a concern?

Today, typical heat pumps and air conditioners use refrigerants R410A or R134A. These refrigerants replaced freon due to their lower ozone depletion potential, but they have very high global warming potential. One kilogram of R410A has a climate impact over 100 years equivalent to 1,923 kgs of CO_2, while for R-134A the ratio is 1 to 1,300. Leakage of these refrigerants during installation, operation or end-of-life disposal poses the risk of undoing some of the lifecycle climate change benefits of using heat pumps. If all refrigerant were lost, lifecycle GHG benefits of heat pumps would be cut approximately in half.

A typical home heat pump or air conditioner system contains 6 kg of R410A, while an HPWH contains 0.8 kg of R134A. Replacing an air conditioner with a heat pump does not increase the risk of refrigerant leakage. A HPWH is comparable to a refrigerator or window AC. Nonetheless, refrigerant risk should be mitigated to maximize the climate benefits of heat pump technology.

The HVAC industry is continuing to research and develop products using lower GWP refrigerants, so the risk will be reduced as new products become available. Low- or zero- GWP refrigerants like ammonia, propane, HFO1234-yf, and carbon dioxide are either available in commercial products or under active consideration by manufacturers. The California Air Resources Board has promulgated regulations for commercial refrigeration, and continues to investigate low-GWP options for refrigeration and air conditioning, which would benefit heat pumps as well. European regulations require a reduction of the total effective GWP of refrigerants sold in the EU to fall to 21 percent of current levels by 2030. This regulation will spur the use of lower-GWP refrigerants and could increase the range of products available in California as well. As these policies progress, refrigerant impacts and risks from heat pumps will fall.

2.3. Market Barriers and Opportunities

There are five primary market barriers to heat pump adoption for space heating:

1. Heat pump technology is unfamiliar to customers, as well as to many installers. Most utility programs do not provide favorable signaling regarding heat pumps.
2. Outdated regulations such as CA's building energy code, which historically favored natural gas-powered space heating equipment as it were deemed to be environmentally preferable to conventional electric resistance equipment (this was resolved in the recent 2019 update of the California building code).

3. Customer economics can be marginal to unfavorable if electric rates are high compared with gas rates, or if rate designs do not appropriately treat heat pump loads. See Section 5.2.

4. Customers tend to replace heating systems with the same kind previously installed, especially under replace-on-failure situations.

5. Heat pump upgrades could require electric panel upgrades for homes without central air conditioning.

The most promising market opportunities for heat pumps in the face of these barriers include:

- New construction or major retrofits, where building heat loads are low, the necessary level of electric service is already required, and the need to install or upgrade gas service in the building could be completely avoided.
- Utility territories where utilities offer incentives for all-electric or electrically-heated buildings.
- Paired installation with building shell improvements (such as air sealing) or as part of an integrated approach to home performance (which may include high performance ductwork) can optimize the comfort and operational cost benefits of a small capacity heat pump.
- Utility territories where electric rates are relatively low compared with gas rates, and in areas where gas service is not available. Heat pumps generally offer very favorable customer economics compared with delivered fuels or electric resistance heat.
- Ductless units can be particularly good complements to hydronic heating, and replacements for wall furnaces and window air conditioners (e.g., in apartments).
- Owners of smaller, low-rise multifamily buildings with ducted gas forced-air systems can replace existing systems with ducted heat pumps. Large multifamily buildings are good candidates for installing other types of heat pump systems such as mini-splits, PTHPs, air-source VRFs, water-source VRFs, water-source heat pumps, or ground-source heat pumps.
- If space limitation is a concern (as with historic buildings), VRF systems are ideal because of their small refrigerant piping and indoor units.
- Buildings with different needs (or needs at different times) in different rooms or areas of the building can be well served by ductless mini-split and VRF systems, which offer advanced zonal control.

3. WATER HEATING

California now has two main technologies to decarbonize its domestic hot water use: heat pump water heaters (HPWHs) and solar hot water heaters (SHWHs) with electric resistance backup. These technologies can be used to replace fossil fuel-based water heaters, or inefficient electric resistance heaters, to accelerate the decarbonization of water heating in the state. HPWHs have become a cost-competitive solution to domestic hot water in many situations due to their superior energy efficiency. The installation of HPWHs is expected to increase substantially for the near future. This is in part due to their proven high efficiency and a recently implemented federal standard that eliminated electric resistance water heaters above 55 gallons for residential applications.[36] SHWHs can also be a viable option. While SHWHs remain expensive for a typical unsubsidized residential-scale project, they may be cost-competitive for multifamily buildings and other commercial facilities with large domestic hot water needs such as hotels, hospitals, or commercial pools.

3.1. Market Opportunity

Residential water heating market

Residential water heating in California accounts for about 25 percent of the total energy use in the residential building sector.[37] Similar to the fuel usage for space heating, natural gas is the dominant fuel for water heating with about 90 percent usage share, followed by propane with about 6 percent, and electricity with about 5 percent.[38] About 40 percent of natural gas use is for water heating, while only 3 percent of electricity is used for hot water.[39] In terms of the number of households, about 85 percent of households use natural gas for water heating, about 10 percent of the households use electricity, and the rest use propane (about 5 percent) and solar (about 1 percent).[40]

The availability of gas services influences the penetration of fuels. Similar to space heating, the northwestern coastal zone (Climate Zone 1) and the mountain region (Climate Zone 16) have substantially lower gas water heater saturation rates (i.e., about 40 percent for Zone 16 and about 7

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[36] See Appliance Standards Awareness Project, "Water Heaters" at https://appliance-standards.org/product/water-heaters for further discussion.

[37] U.S. Energy Information Administration, Residential Energy Consumption Survey 2009. Table CE3.5

[38] Id. Table CE4.5

[39] Ibid.

[40] RECS 2009; KEMA (2014) 2012 California Lighting and Appliance Saturation Survey (CLASS).

percent for Zone 1).[41] These regions have a high saturation rate for electric resistance heaters. HPWHs can be highly cost-effective options for consumers replacing electric resistance heaters.[42]

Commercial water heating market

Commercial water heating accounts for about 12 percent of commercial sector energy use and 32 percent of natural gas use.[43] Natural gas accounts for about 95 percent of energy use for water heating according to the California Commercial End-Use Survey. The commercial sector has slightly less opportunity for replacing electric resistance heating with HPWH than do residential applications because commercial buildings have been less likely to rely on resistance for water heat: 1 percent of commercial electricity goes to provide hot water versus 3 percent of residential electricity.

Among various commercial facilities, the largest energy savings potential exists in lodging, health, and restaurants in terms of absolute energy savings because the water heating energy usage for these three types comprises more than half of all commercial hot water demand (17 to 18 percent for each type). Hot water is the largest component of lodging energy use (62 percent). It is also a particularly large use in health (38 percent), schools (25 percent), and restaurants (22 percent).[44] These will be markets particularly in need of cost-effective ways to decarbonize hot water.

3.2. Technologies: Heat Pump Water Heaters

Introduction to HPWH

Electric heat pump water heaters have become a prime candidate to help decarbonize energy use for domestic water heating in the United States due to their high efficiency, potential use of low- or zero-carbon electricity, and cost-competitiveness. Like electric heat pumps for space heating, HPWHs use a vapor-compression cycle to move heat from one place to another and produce hot water. Thus, the efficiency of HPWHs is typically two to three times more efficient than conventional electric resistance heating. The database of ENERGY STAR-certified hot water heaters lists some HPWH models with uniform energy factors over 3.5.[45,46]

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41 KEMA (2014) 2012 CLASS, Table 8-2 and Table 8-4.

42 Based on Federal EnergyGuide sheets for 50 gallon HPWH and resistance water heaters available for sale at major retailers, payback periods can be less than 3 years at the national average electricity cost of 12 cents/kWh.

43 2006 California Commercial End-Use Survey (CEUS)).

44 2006 California Commercial End-Use Survey (CEUS)).

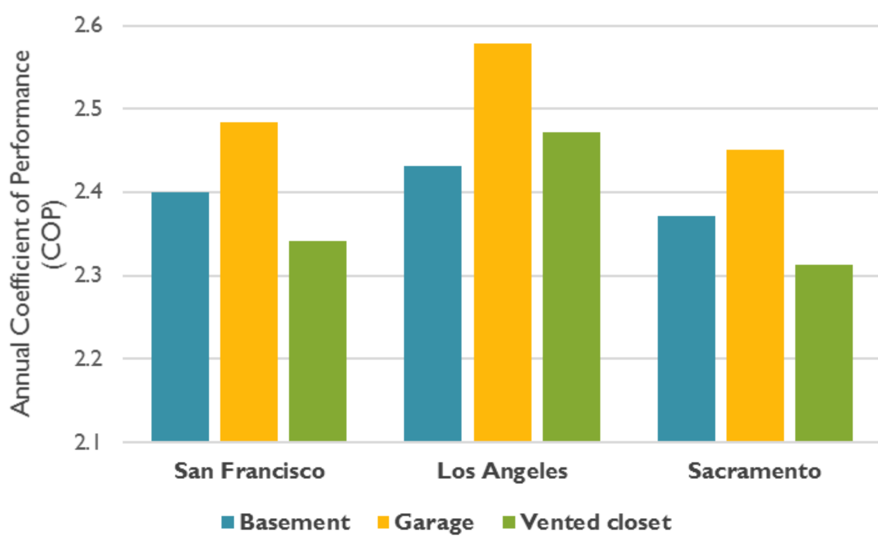
45 https://www.energystar.gov/productfinder/download/certified-water-heaters/.

46 Uniform Energy Factor (UEF) represents an efficiency of a product under specific test conditions defined by U.S. EPA. Xx check this definition xx

Most residential HPWHs are hybrid HPWH systems that combine heat pumps, backup electric resistance elements, and hot water storage tanks. While HPWHs are very energy efficient, the rate of hot water production (i.e., the recovery rate of hot water) is slower than electric resistance systems. For example, the 50 gallon Rheem Professional Prestige HPWH without resistance offers 53 gallons in the first hour and 16 gallons per hour of recovery, while the same HPWH with resistance heating assist offers 67 gallons in the first hour and 29 gallons per hour of recovery.[47]

HPWH performance depends on where it is installed because the system pumps heat out of the ambient air around the unit. In California, HPWHs are typically installed in the garage for optimal performance, but they can also be installed in other locations such as basement, back porch, backyard, and outdoor-vented closet. When installed inside the building, additional ductwork to supply air to the units may be required, and the HPWH can cool the building, resulting in the need to replace that heat during the heating season.[48] When ambient air temperature is very low, HPWH performance degrades substantially, so outdoor installations are typically not recommended except in warm climates. Among basement, garage, and vented closet options, an NRDC study shows that the garage leads to the highest average performance in California climates, as shown in Figure 7.[49]

Figure 7. Annual performance of hybrid HPWH by installation location in a subset of California climates



Source: Pierre Delforge (2017). "Electric Heat Pump Water Heater Performance Simulation," NRDC.

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[47] Rheem Water Heating. Specification sheet for Rheem Professional Prestige Hybrid Electric. Accessed Sept. 10, 2018 at http://cdn.globalimageserver.com/FetchDocument.aspx?ID=0ff25606-fc65-4deb-b959-bfdfd1599eb0

[48] Replacement heat is not necessarily one-for-one. For further analysis, see NEEA, 2017, "Interaction between Heat Pump Water Heaters or Other Internal Point Source Loads and a Central Heating System," available at https://neea.org/img/uploads/interaction-between-heat-pump-water-heaters-and-heating-system.pdf.

[49] Pierre Delforge (2017). "Electric Heat Pump Water Heater Performance Simulation," NRDC. Accessed via https://www.nrdc.org/experts/pierre-delforge/very-cool-heat-pump-water-heaters-save-energy-and-money.

HPHW in multifamily and commercial buildings

For multifamily and commercial buildings, HPWH configurations can be quite different from single-family homes. Multifamily buildings with central hot water service can be served by appropriately sized commercial HPWH products or groups of residential-scale products hooked together to serve a common load. Unitary hot water in multifamily buildings is similar to single family, although the kinds of spaces available to locate the HPWH may be different (e.g., there may be no attached garage for each unit).

Where available, HPWHs can be installed on a roof, or in a garage, basement, or mechanical room. If a building has a below grade garage, it can be an optimal place to house HPWHs because temperatures in such a place are milder than outdoor. This placement enables HPWHs to perform much better in cold months.[50] Mechanical rooms or laundry rooms in any building can be a fortuitous place for HPWHs if such rooms are currently too hot or too humid, as HPWHs cool and dehumidify the air around them.[51] Space may be an issue with laundry rooms, but creative solutions exist: In one case, a hospital mounted an HPHW on the ceiling of the laundry room.[52] Further, certain commercial facilities such as spas, restaurant kitchens, or wastewater treatment facilities produce waste heat that can be utilized to improve the performance of HPWHs. Generally, HPWHs are suitable for any facilities that have simultaneous demand for water heating and space cooling.

The availability of large HPWH models is limited compared to residential products, but several companies currently offer large scale-HPWH products in the U.S. market. Heat recovery chillers are a kind of heat pump suitable for large and institutional buildings with a central cooling system. A standard chiller system rejects heat to the outdoors through a cooling tower on the roof. A heat recovery chiller can recover some of the wasted heat from electric chiller systems and redirect the heat for producing hot water.[53]

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[50] A 2015 study by Ecotope evaluated two pilot installations of one type of HPWH called Reverse Cycle Chiller in multifamily buildings (one 6-story building with 118 units and one 7-story with 215 units) in Seattle, Washington. It found the parking garages provided significant performance benefits for the heat pumps by maintaining relatively high temperatures throughout the year (the temperature did not drop below 48-50F). For detailed info, see Ecotope. 2015. RCC Pilot Project: Multifamily Heat Pump Water Heaters in Below Grade Parking Garages in the Pacific Northwest.

[51] See examples of installations of Colmac's HPWHs at https://static1.squarespace.com/static/551cc019e4b0e383d175e871/t/55ac1e83e4b019ea0d5d70e7/1437343363107/05_CWH_Case+Studies_041614.pdf

[52] Ibid.

[53] Alan Meier et al. 2018. University of California Strategies for Decarbonization: Replacing Natural Gas, p. 76. Available at http://dms.hvacpartners.com/docs/1001/Public/0A/04-581025-01.pdf.

Carbon dioxide HPWHs

Some HPWHs rely on carbon dioxide (CO_2) as a refrigerant instead of commonly used refrigerants (such as R134A). CO_2-based HPWHs do not need auxiliary electric resistance elements.[54] This type of HPWH was first commercialized in Japan in 2011 and has become the most popular system in that country.[55] In fact, as of February 2016, these systems have a 98 percent market share among all new HPWHs in Japan.[56]

In the United States, at least two CO_2-based HPWH models are now available: one commercial-scale HPWH from a Japanese company called Maekawa, and one residential-scale product available from Sanden USA.[57] Sanden's HPWH system is a split system with an outdoor compressor, so it can be located more flexibly within the living space. A CO_2-based HPWH system has several advantages over hybrid HPWH models. The use of CO_2 allows the system to operate more efficiently, with COPs of as high as 4, and to produce hot water efficiently down to an ambient air temperature of -20°F.[58] The use of CO_2 also allows the system to produce hot water up to 175°F, significantly higher than heat pumps based on HFC refrigerants.[59] Further, because a CO_2-based HPWH does not require an electric resistance backup element, it only needs 15 Amp electric service. In some cases, this could help to avoid electrical upgrade costs.

Despite all of these potential benefits of the CO_2 HPWH, the uptake of this technology by consumers (especially residential customers) is unclear for the near term. Its total installed cost is currently higher at about $4,500, more than twice the total installed cost of hybrid HPWHs.[60] On the other hand, CO_2 HPWHs may find niche markets among certain commercial customers with large hot water loads and/or high temperature requirements (for instance, hotels, hospitals, commercial pools, restaurants, or multifamily buildings). Further, the price is expected to come down economies of scale in the future as CO_2 HPWHs gain more market share.

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[54] For example, the Sanden $SANCO_2$ 50 gallon HPWH has a first hour rating of 69 gallons, more than matching the performance of the Rheem HPWH with resistance assist discussed above. See https://www.sandenwaterheater.com/sanden/assets/File/SANDEN_CO2WaterHeater_9_16.pdf.

[55] http://www.r744.com/articles/7084/co_sub_2_sub_heat_pumps_bringing_natural_refrigerants_to_japanese_homes

[56] 2016 Guide to Natural Refrigerants in Japan – State of the Industry, http://publication.shecco.com/publications/view/65

[57] Ecotope (2015) RCC Pilot Project: Multifamily Heat Pump Water Heaters in Below Grade Parking Garages in the Pacific Northwest.

[58] Steven Groves. 2018. "Mitigating the Parasitic Effect of Heat Pump Water Heaters on Home Heating Systems in Cold Climates" Fortis BC. Presentation at the 2018 ACEEE Hot Water Forum, March 21, 2018.

[59] https://www.sandenwaterheater.com/sanden/assets/File/Sanden_sanc02_technical-info_10-2017_4.pdf; https://zeroenergyproject.org/2017/05/22/co2-takes-heat-pump-water-heaters-next-level/

[60] The product price is about $4,000, https://foursevenfive.com/product/sanco2/ . Assuming the installation labor cost $500, the total installation cost would be about $4,500.

3.3. Market Barriers and Opportunities for HPWH

There are six primary market barriers to HPWH adoption:

1. HPWHs require access to a sufficient volume of air, which means they must either be installed in a large enough room (such as a basement, large laundry room, or garage) or be ducted to the outside. This complicates replacement, in particular, if existing gas or electric dryers are not located within sufficient air volume. This can increase cost or otherwise complicate installation. HPWHs cool the space they are in, which can result in increased heating load in the winter.

2. HPWHs are an unfamiliar technology, and customers replacing water heaters typically replace in kind.

3. Building energy codes have favored tankless gas water heaters, requiring additional analysis to justify a HPWH.

4. Overall lifecycle cost of choosing a HPWH over a gas WH vary from very favorable to unfavorable, depending on rates and efficiency. See Section 5.2.

5. HPWH upgrade could require an electric panel upgrade, although there are an increasing number of options which require only an additional 15 A circuit. [61]

6. HPWHs are perceived as being noisy. High performance HPWHs make about as much noise as a refrigerator.[62]

The most promising market opportunities for HPWH in the face of these barriers include:

- New construction, where the location of the water heater can be optimized for HPWH requirements, there is no "replace in kind" barrier, and the necessary level of electric service is already required.

- Utility territories where electric rates are relatively low compared with gas rates, or where gas service is not available.

- Multifamily buildings, where larger tanks (which help to avoid the need for electric resistance to supplement the heat pump) and "ganged" water heaters (multiple smaller units used in parallel) can effectively meet multiple units' needs

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[61] Typical hybrid HPWHs require 30 Amps, but Sanden CO_2 HPWHs use 15 Amps and Rheem has recently introduced models that require only 15 Amp service at the cost of slower recovery after periods of high usage.

[62] NEEA Advanced Water Heater specification, https://neea.org/img/documents/advanced-water-heater-specification.pdf.

3.4. Technologies: Solar Hot Water

Solar hot water (SHW) systems use the heat of the sun to directly or indirectly heat water. The water is then stored in a high-temperature storage tank before blending into a traditional hot water heater to deliver domestic hot water at an appropriate temperature. SHW systems work for both domestic hot water and space heating, but the majority of SHW projects are designed and sized to serve domestic hot water only. SHW requires a backup water heating source during the winter when solar insolation is insufficient. The fraction of domestic hot water needs that a SHW system can supply is called a solar fraction. In California, an average solar fraction ranges from 70 to 80 percent, with a seasonal range between 25 percent and 95 percent.[63] The remaining domestic hot water needs are typically met by natural gas or electric resistance heat.

SHW systems are relatively expensive. However, they could be good investments with available financial incentives, especially for certain commercial customers with large and constant domestic hot water needs. As discussed in the HPWH section, commercial sectors with the largest savings potential are lodging, health, and restaurants. In these building types, hot water energy use accounts for 20 to 60 percent of the total building energy use. In addition, multifamily buildings, laundromats, and car washes are ideal as they have large, constant hot water demands. Roof space is not likely a major limitation for these buildings as many of them are low-rise buildings with flat roofs.[64] For taller buildings, roof space for collectors and hot water storage and running pipes can be problematic.[65]

SHW is a relatively mature technology with decades of performance. The technology is very common in China, Australia, the Middle East, and Europe. China has installed about 70 percent of the world's total solar hot water systems with the largest penetration rate in the world.[66] In contrast, the United States and Canada have only about 3 percent of the penetration rates achieved in China and less than 10 percent of the rates in Australia, Middle Eastern countries, and Europe. Since 2010, California has installed about 6,000 SHW systems for households, and 3,500 for businesses through the state initiatives.[67]

[63] National Renewable Energy Laboratory. 2011. Break-even Cost for Residential Solar Water Heating in the United States: Key Drivers and Sensitivities, Appendix C and Appendix F.

[64] Robb Adrich and James Williamson, 2016. Role of Solar Water Heating in Multifamily Zero Energy Homes, P. 5.

[65] Id.

[66] International Energy Agency. 2017. Solar Heat Worldwide – Global Market Development and Trends in 2016, Figure 32, Available at https://www.iea-shc.org/data/sites/1/publications/Solar-Heat-Worldwide-2017.pdf

[67] CSI Thermal Incentive program database, http://www.csithermalstats.org/download.html

3.5. Market barriers and opportunities for SHW

A 2009 study on California's SHW pilot program identified the following barriers to SHWs in California: [68]

1. high upfront capital costs;
2. lack of knowledge of SHW;
3. permitting costs and requirements; and
4. lack of a well-developed SHW workforce.

The state promoted SHW for the past decade through state incentives, utility programs, and federal tax credits, and thereby increased the installation of SHW systems. However, high upfront capital costs remain a major barrier: the installed costs of SHW systems have not experienced any cost reduction over 10 years of data collected by the California Solar Initiative (CSI) Thermal Incentive program.[69]

The most promising market opportunities for HPWH in the face of these barriers are commercial applications, when paired with existing incentives from the CSI Thermal Incentive Program. Table 1 provides customer economics in terms of simple payback for three business case studies for car wash, laundromat, and microbrewery businesses, available from the CSI Thermal Program website. With various financial incentives, payback years could be 4 years to 13 years depending on business types, with shorter payback periods for facilities with larger domestic hot water demand.

Table 1. Commercial SHW customer payback examples

	Car wash	Laundromat	Microbrewery
System cost	$49,080	$144,000	$64,000
CSI rebate	$29,114	$113,629	$33,657
Federal ITC	$5,990	$9,111	$9,103
System Cost Less CSI Rebate & ITC	$13,976	$21,260	$21,240
Annual energy savings (at $1/therm)	$1,442	$5,628	$1,667
Simple payback with incentives	**10**	**4**	**13**
Simple payback without incentives	**34**	**26**	**38**

Source: Center for Sustainable Energy, CSI-Thermal Program Contractor Resources.

[68] California Center for Sustainable Energy. 2009. Solar Water Heating Pilot Program: Interim Evaluation Report.

[69] The average cost of a residential system ranges from $8000 to $10,000 over the decade, without a clear long-term trend toward lower costs or higher performance. For details, see CSI Thermal Incentive Program database at http://www.csithermalstats.org/download.html

4. OTHER APPLIANCES

In California, space and water heating represent the largest opportunities for decarbonization through electrification and efficiency improvements in the residential sector. Stoves and clothes dryers account for nearly all the remaining natural gas consumption in the residential sector. For residents who wish to fully eliminate fossil fuel emissions or simply build or transition to all-electric homes, there are efficient electric options for these other end uses.

Table 2: Electricity and natural gas consumption from dryers and stoves

	Dryers	Stoves
Electricity		
- **Annual Unit Energy Consumption (kWh)**	652	262
- **Saturation (%)**	44%	30%
- **% of residential electricity consumption**	4%	4%
Natural Gas		
- **Annual Unit Energy Consumption (Therms)**	25	34
- **Saturation (%)[70]**	46%	73%
- **% of residential natural gas consumption**	3%	7%

Source: RASS 2009. Note: The percent of electricity consumption given for dryers also includes washing machines, and the percent given for stoves also include dishwashers.

Both stoves and clothes dryers are large, expensive appliances with limited turnover. The biggest opportunity for switching to more efficient appliances is at the time of initial construction or during home renovations. The market for new construction has been steadily recovering in California since the economic downturn in the late 2000s and reached a 10-year high in 2017 with 113,320 new units.[71]

4.1. Cooking

The most common residential cooking set-up today is a stove or range, defined as a unit with both an oven and cooktop. The cooktop and the oven can be purchased separately, and with the exception of induction cooktops (which are always electric), stoves, convection ovens, and cooktops can be either gas or electric. Cooking appliances account for 4 percent of residential electricity consumption, and 7 percent of natural gas consumption.

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70 Saturation of homes with natural gas accounts

71 Includes single-family and multi-family units. US Census, Building Permits Survey. Table 2u. New Privately Owned Housing Units Authorized Unadjusted Units for Regions, Divisions and States. https://www.census.gov/construction/bps/

In the Pacific census region,[72] fuel sources are evenly split between electricity and natural gas for combined stoves (see Table 3). With separate cooktops, that balance shifts towards natural gas, and with separate wall ovens the mix shifts towards electricity.

The average life of a range is 13 to 15 years.[73] Because cooking can be an integral part of a customer lifestyle, stove upgrade and replacement decisions are generally driven by performance considerations and cost, with energy consumption a secondary consideration.

Table 3: Cooking appliance ownership and fuel source in the Pacific region

	Ownership %	Fuel Source	
		Electricity	Natural Gas or other fuel
Stove	89%	47%	53%
Separate cooktop	18%	38%	63%
Separate wall unit	15%	81%	19%
Microwave oven	96%	100%	0%
Outdoor grill	55%	0%	100%

Note: Outdoor grill "other fuel" includes charcoal grill. Source: RECS 2015.

Potential electric alternatives

Electric induction cooktops and convection ovens can meet customers' performance expectations while also increasing efficiency and lowering GHG emissions. Glass ceramic cooktops, which generate heat through electric resistance, do not provide the efficiency benefit of induction, but do provide an affordable alternative to gas. Equipment replacement may also be accompanied by kitchen renovation, which provides an opportunity to wire for electric appliances.

Induction cooktops and ranges:

Status of the technology: Induction cooktops are different than traditional electric cooktops in that the surface element heats the pot through an electromagnetic field rather than through radiant heat. (The oven on an induction range is the same as other electric ovens.) The induction process is faster and inherently more efficient, with 90 percent of the energy consumed transferred to the food, compared to

[72] California, Oregon, Washington, Alaska, and Hawaii.

[73] National Association of Home Builders (NAHB) and Bank of America, Study of Life Expectancy of Home Components. February 2007. https://www.interstatebrick.com/sites/default/files/library/nahb20study20of20life20expectancy20of20home20components.pdf

74 percent for traditional electric and 40 percent for gas stoves.[74] Consumer Reports found induction cooktops to consistently perform as well or better than other electric units, ranking induction cooktops among some of the highest scoring ranges and cooktops.[75] As with other electric cooktop options, induction cooktops produce no combustion gases in the kitchen, improving indoor air quality.

Market barriers: There are four main market barriers to adoption of induction cooktops:

1. Bias or preference: some people have a strong preference for gas-powered units because of both real and perceived trade-offs in switching to an electric resistance one;

2. Cost: the prices for induction range and cooktops have been coming down, however they are still more expensive than glass-ceramic electric units; upgrade from gas to electric can also require a new high-amperage circuit and associated space in the electrical panel;[76]

3. Magnetic cookware: they require pots and pans that include steel or iron, which may require users to upgrade; and

4. Performance: they lack an actual flame to char and the magnetic field can interfere with digital thermometers.

Because cooking is not simply utilitarian but also part of one's lifestyle, bias, perceptions, and preference should not be discounted. Many customers already prefer using diverse cooking options – cooktop, grill, microwave, and oven. Pairing induction with a grill or single-ring gas may meet customer expectations for different kinds of cooking performance.

Market status: While the price of induction stoves is still higher than that of traditional electric stoves, customer adoption is slowly rising. Research and Markets, Inc., projects a 5.1 percent compound market growth rate for induction cooktops in North America through 2023.[77]

Additionally, standalone single-burner induction cookers are available and affordable (less than $100) to supplement a gas range or other cook-top. These cookers allow users to try induction before committing to a new range, without requiring the user to fully switch-out their cook-top.

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[74] Sweeney, M., J. Dols, B. Fortenbery, and F. Sharp. "Induction Cooking Technology Design and Assessment." Electric Power Research Institute (EPRI). 2014. https://aceee.org/files/proceedings/2014/data/papers/9-702.pdf

[75] Consumer reports, Pros and Cons of Induction Cooktops and Ranges. May 2017. https://www.consumerreports.org/electric-induction-ranges/pros-and-cons-of-induction-cooktops-and-ranges/

[76] Prices for 30" cooktops at HomeDepot.com as of Sept. 14, 2018, begin at $398 for glass ceramic and $699 for induction.

[77] North America Household Induction Cooktops Market (2017-2023), Research and Markets. Summary available at https://www.researchandmarkets.com/research/3kz283/north_america..

Convection ovens:

Status of the technology: Convection ovens, also known as fan-assisted ovens, are ovens that use both a traditional heating element and a fan to circulate the air around the food. Because it has a fan, a convection oven distributes heat around the food, allowing it to cook more evenly, more quickly, and at a lower temperature than with a conventional radiant oven. This results in faster preheating and lower cooking times. Convection ovens can use 20 to 30 percent less energy than traditional electric ovens according to the American Council for an Energy-Efficient Economy (ACEEE).[78]

Market barriers: The two main market barriers for convection ovens are:

1. Cost: the up-front cost can be higher than for a traditional oven; and
2. Customer familiarity and expectations: the user may have to adjust recipes to account for the different cooking time, and the fan can interfere with bread's ability to rise.

Market status: Currently, ENERGY STAR does not label residential ovens, so it can be hard for customers to understand the tradeoffs between different types of ovens and the implications of the different fuel types. Convection ovens hold a plurality market share lead in commercial ovens, due to the ability to quickly deliver uniform products.[79]

4.2. Laundry

Clothes dryers (combined with washers) account for 4 percent of residential electricity consumption and 3 percent of residential natural gas consumption in California.[80] While dryers only account for a small portion of total annual electricity consumed in California, they do have a high power draw. This means they have an outsized capacity impact on the electricity system when used during peak hours. There are three main types of clothes dryers that are broadly commercially available in the United States: electric (resistance) dryers, gas dryers, and heat pump electric dryers.

As with stoves, there is limited pace of equipment turnover with clothes dryers. The average life of a clothes dryer is 13 years for both gas and electric units.[81] Replacement decisions are generally driven by machine quality and cost, where energy use and savings can be an important consideration.

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[78] Energy Savings Tips, Smarter House. https://smarterhouse.org/cooking/energy-saving-tips.

[79] Convection Oven Segment to Dominate the Global Commercial Oven Market Through 2021: Technavio. Business Wire. https://www.businesswire.com/news/home/20161216005103/en/Convection-Oven-Segment-Dominate-Global-Commercial-Oven.

[80] 2009 Residential Appliance Saturation Survey. California Energy Commission. http://www.energy.ca.gov/appliances/rass/.

[81] National Association of Home Builders (NAHB) and Bank of America, Study of Life Expectancy of Home Components. February 2007. https://www.interstatebrick.com/sites/default/files/library/nahb20study20of20life20expectancy20of20home20components.pdf

Potential electrification alternatives

The energy efficiency of electric dryers has increased with the use of sensors to avoid over-drying clothes. However, alternate means of drying can increase efficiency by substantially more than this incremental improvement. These options include condensing dryers and heat pump dryers. Condensing dryers use cool ambient air to cool the warm wet air from the dryer drum, condensing the water and returning drier air to the clothes, to repeat the loop. Single appliances that both wash and dry typically use a condensing cycle. Heat pump dryers are even more efficient, because the condenser is cooled as heat is pumped into the drum. Both of these types of dryers can be ventless, but only heat pump dryers are also available at the larger size typically used in American homes. We focus on heat pump dryers here because of their greater efficiency and larger size availability.

Heat pump dryers

Status of the technology: A traditional electric resistance clothes dryer operates by heating cool air, blowing it into the drum chamber where the wet clothes are, and then venting moisture laden hot air out of the building. A heat pump electric clothes dryer uses a dehumidifier to condense water out of the circulated air. This water is then pumped to the same drain used by the clothes washer. Hybrid heat pump dryers have an electric element to increase drying speed and are typically vented the same as conventional dryers. Heat pump only dryers rely only on the vapor compression cycle dehumidifier to heat the circulated air and remove moisture and do not have an exhaust vent as all moisture is condensed and captured.

Heat pump electric clothes dryers use 55 percent less electricity than traditional electric resistance clothes dryers and 30 to 40 percent less electricity than efficient ENERGY STAR-rated electric resistance clothes dryers.[82, 83] Customer savings can be magnified when paired with a high efficiency clothes washer, which extracts more moisture from the clothes than a traditional washing machine, reducing drying time and total laundry energy use. Some heat pump clothes dryers are ventless, meaning that the building seal does not need to be penetrated to vent the dryer and the dryer does not blow conditioned air out of the building. Heat pump dryers are also slightly gentler on clothes because they operate at a lower temperature, placing less strain on fabrics.

[82] 2018 Energy Efficiency Potential and Goals Study for 2018 and Beyond. Prepared for California Public Utilities Commission. MICS database. http://www.cpuc.ca.gov/General.aspx?id=6442452619

[83] Eric Martin, Karen Sutherland, and Danny Parker. "Measured Performance of Heat Pump Clothes Dryers." ACEEE Summer Study on Energy Efficiency in Buildings, 2016. https://aceee.org/files/proceedings/2016/data/papers/1_160.pdf

Market barriers: There are three potential market barriers to heat pump clothes dryer adoption:

1. Cost: heat-pump clothes dryers are still more expensive then ENERGY STAR-rated gas or electric clothes dryers;[84]
2. Unfamiliarity: they have only been on the market in the United States for a few years, so customers and contractors are not broadly familiar with them yet; and
3. Drying time: they can take longer to dry clothes than a traditional electric or gas dryer.[85]

Each of these barriers can be addressed as the technology advances and more models become available for the U.S. market. The need to re-plumb (for gas) or re-wire (for electric) is a barrier to switching equipment type when replacing a dryer.

Market status: Heat pump clothes dryers have been available in Europe for many years, but they only became readily available in the United States starting in 2014 and 2015. European imported dryers tend to be small (e.g., 4 cubic feet), while Whirlpool and LG offer dryers that match U.S. customer expectations for dryers over 7 cubic feet. Energy Star labels clothes dryers, so there is some market information available for customers indicating energy savings.

[84] On the website of appliance retailer A.J. Madison, ENERGY STAR electric resistance dryers begin at about $700, while heat pump dryers begin at around $1,100. https://www.ajmadison.com/ accessed Sept. 13, 2018.

[85] Northwest Energy Efficiency Alliance. 2018. *Heat Pump Clothes Dryers in the Pacific Northwest – Abridged Field & Lab Study Report*. https://neea.org/img/documents/Heat-Pump-Clothes-Dryers-in-the-Pacific-Northwest.pdf

5. Residential Customer Economics of Decarbonization

Residential customers who adopt clean heating technologies will create corresponding shifts in their energy spending. Deploying a combination of energy efficiency, electrification, and load management will result in some increased and some reduced costs. We calculated the cost impacts of pursuing decarbonization for four building types in each of three climate zones. The four building types are:

1. Single-family existing home retrofits with heat pump space and water heating replacing natural gas systems at the end of their useful life;
2. New construction of an all-electric single-family home;
3. Multifamily existing home retrofits with heat pump space and water heating replacing natural gas systems at the end of their useful life; and
4. New construction of an all-electric multifamily home.

For each case, we analyzed two bounding cases. The first, a base case, assumes no building shell improvements and uses the more commonly available rate design for each utility. The advanced case takes a more comprehensive approach, including load management for the water heater, time of use rates with greater peak/off-peak price differentials, and in retrofit cases some building shell improvements. In both cases, we assumed that homes would have the high-efficiency air conditioning that comes with high efficiency heat pumps. The new construction cases do not have shell improvements because a new building would already meet stringent building energy code requirements. No appliance or system costs include utility incentives.

We used some of the more efficient ASHP and HPWH equipment currently available on the market, because this study is intended to be forward looking and it is reasonable to assume that today's efficient equipment will become the market norm over the next 10 years, particularly as California adopts market development policies that focus on high-efficiency equipment in order to maximize the customer, grid, and environmental benefits of electrification.

We examined these homes in Climate Zones 3, 9, and 12, corresponding to the Bay Area, the Los Angeles Basin, and Sacramento. We selected these regions because together they reflect most of California's population, while offering diversity in both climate and electric and gas utilities. We used the most relevant existing electric and gas rates for each area, from Pacific Gas and Electric (Bay Area), Southern California Edison and Southern California Gas (LA Basin), and Sacramento Municipal Utility District and PG&E (Sacramento).

Table 4. Building configurations examined in this analysis. See Appendix for details and costs by measure.

	Base		Advanced	
	Retrofit	**New**	**Retrofit**	**New**
Building shell	No change	Title 24 compliant	14% improvement	Title 24 compliant
Rate design	Current default		Most dynamic option available	
AC efficiency	13 SEER		18 SEER	
HP efficiency	10.5 HSPF		10.5 HSPF	
HPWH efficiency	3.7 UEF		3.7 UEF	
PV capacity range	1) None 2) Offset full electric bill	1) Offset electric bill of gas home 2) Offset full electric bill	1) None 2) Offset full electric bill	1) Offset electric bill of gas home 2) Offset full electric bill
Cooktop	No change (gas)	Induction	No change (gas)	Induction
Dryer	No change (gas)	HP dryer	No change (gas)	HP dryer
Gas infrastructure	No change	Fully avoided	No change	Fully avoided
Electric infrastructure range	1) No upgrade 2) Panel and circuit upgrade required	Designed and wired for all-electric	1) No upgrade 2) Panel and circuit upgrade required	Designed and wired for all-electric

5.1. The Impact of Rate Design

Electric system costs vary over time, as peak demands drive more expensive generation as well as transmission and distribution costs. Rates that do not vary in time average over these variations, and recover appropriate costs from average customers with typical load shapes. However, these flat rates can overcharge higher-consumption customers with loads that are concentrated away from peaks—such as homes with efficient electric space and water heating. Time-varying rates with substantial peak to off-peak differentials can reduce this subsidy and more accurately reflect infrastructure and generation costs that are driven by peak loads.[86] These rates also offer the prospect of lower rates in all other times, which makes heat pump operation more cost-effective during those times. While rates that closely reflect marginal costs in the context of high penetration of solar PV are not widely available in California yet, PG&E and San Diego Gas & Electric have implemented whole-home electric vehicle rates that have some of the same characteristics, and SCE and SMUD offer opt-in rates that are closer to reflecting this reality than the most commonly available rates.

[86] Highly differentiated rates can be problematic for low-income customers who live in inefficient buildings in hot climates, and for whom cooling is a health issue. Highly differentiated rates could have health impacts and should be optional.

A Note on Electrical Service Upgrades

A home's electrical service is designed to meet the maximum expected coincident current demanded by all of the home's electrical appliances. The most common levels of residential electrical service are 200 Ampere (A), 100 A, and 60 A. New homes have been built with 200 A service as the default for a number of years, and the 2013 California Energy Code required this level of service (in part to ensure that service sufficient to charge an electric vehicle is available).

For an all-electric home, 200 A service is generally more than adequate, including capacity to charge an electric vehicle. For a home that uses natural gas for space and water heating, however, lower levels of service are commonly sufficient. In California's warmer climate zones where air conditioning is common and a source of substantial demand, 60 A service is likely insufficient even for a home that otherwise uses gas for its most energy-intensive end uses.

The question we must address is under what circumstances the upgrade of space and water heating to heat pump-based electrical appliances would trigger the need for an electric service upgrade. Such an upgrade can cost more than $4,000, so if it is required it would have a substantial impact on the cost-effectiveness of switching to heat pumps. Upgrade to heat pumps for water or space heating that triggers the need for an electric service upgrade would also create a substantial additional barrier in an urgent replacement situation when an existing appliance breaks. It is also important to consider that while heat electrification may be the trigger for a panel upgrade, the upgrade also supports the future installation of an electric vehicle charger, and therefore cannot be entirely attributed to heating electrification.

Because not all appliances are expected to draw their peak demand at the same time, the National Electric Code defines a set of demand factors to scale the peak current for different kinds of appliances. Water heaters, for example, are scaled by 75 percent. Heating and air conditioning systems don't run at the same time, so the service is designed to meet the larger of their two demands.

Heat pump water heaters are available in 15 A and 30 A variants, which would add 11.25 A or 22.5 A, respectively, to the required electrical service. The 30 A variant is the more common model, but the 15 A serves the specific need of allowing a HPWH switch with a greater likelihood of avoiding service upgrades. For homes without air conditioning, adding a heat pump would typically add about 20 A to the required service. For homes with air conditioning, adding a heat pump may have no effect (if the AC draws more power than the heating side at design conditions), or may require an increased level of service if the heating side draws more. Note that the point of comparison is the power draw of the installed (generally older and less efficient) air conditioner and its associated blower, so an increase in capacity to meet a heating need does not necessarily mean an increase in peak power draw.

To model customer economics, we selected two rates from each utility – one for the base case and one for the advanced case. The rates we selected are shown in Table 5. In each case we used any available version of the rate designed for electric heating or all-electric homes; these variants typically have larger baseline allowances.

Table 5. Electric rates used for analysis of customer economics

	Base	Advanced
PG&E	E-TOU-C3	EV-A
SCE	TOU-D 5-8 PM	TOU-D-B
SMUD	R	R-TOD

For multifamily, we assumed that the residents would be eligible for CARE rates for both electricity and gas. PG&E does not offer a CARE option for the whole home EV rate, so we adjusted the distribution portion of that rate to parallel how it is adjusted for the time of use CARE rates EL-TOU-C3. For gas rates, we used Rate G-1 from PG&E in the Bay Area and Sacramento and Rate GR from SoCal Gas in the LA Basin, along with their associated CARE discounts.

Across all locations, using the rate with larger peak/off-peak differentials lowers low-emission homes' annual energy bills, and better reflects the costs these customers cause in the electric system. The rates available today are not optimized to reflect the costs caused by all-electric homes. This gives us some confidence that if utilities develop rates designed for buildings with electric space and water heating, and the tools to automatically shift loads in response to those rates become more broadly available, electrification would lower bills for more Californians.

5.2. Results: Customer Costs and GHG Emissions

Customer economic analysis presents no clear-cut favorite when comparing homes with gas heat and appliances with those with electric systems. Electric homes are better able to take advantage of net metering, so electric homes with solar PV optimized to the load offer attractive customer economics in all modeled cases. The energy use in the buildings that we modeled is typical of each type—but the circumstances facing each individual building will be unique. Looking at the results of this analysis as a whole, we believe that many building owners and occupants will find that decarbonizing their buildings with electrification and efficiency makes economic sense today. However, others may face higher costs until further price declines or performance improvements in electric systems, incentives, additional energy efficiency measures to reduce heating and cooling energy needs, availability of load management programs, or rate designs that better reflect the load shape of electrically heated buildings make electric solutions more cost-effective. The combination of electric and gas rates in Sacramento is more favorable to electrification, as a general matter, than rates in the Bay Area or LA Basin.

For each of the building types we examined, we calculated the resulting annual GHG emissions for the gas home and the electric home.[87] Residents that choose electric space heating, water heating, or all-electric homes will substantially reduce the GHG emissions from their energy use, and that reduction will increase over time as California's electric grid decarbonizes.

Single-family retrofit

Decarbonization generally increases capital cost relative to the base case, unless the home is in need of a new air conditioner and does not need any electrical upgrades. The increased solar PV to optimize savings results in additional capital cost, but with optimized solar PV, all of the decarbonized homes save more than $200 per year on their energy bills.

Customer lifecycle cost differences between gas and low-emission homes over 20 years, taking into account both upfront capital and operating cost differences, range between a net cost of $9,700 and net benefit of $7,300. This analysis and the parallel results presented in the remainder of this chapter assume a 5 percent real discount rate and a constant inflation-adjusted operating cost difference between decarbonized and gas-heated homes. We do not include any difference in maintenance or removal costs. On general across climate zones, savings are greater in more efficient homes using advanced rates and optimized solar PV. As Table 6 shows, upfront capital costs also have a substantial effect on lifecycle costs: Net benefits are greatest if a home benefits from the simultaneous cooling system replacement that comes with heat pump installation ("full value for AC") and does not require an electrical panel upgrade.

[87] We assumed emission factors of 5.3 kg/therm for natural gas and 0.28 kg/kWh for grid electricity (based on a 50 percent renewable electric supply over the life of the appliances and assuming a generic natural gas plant provides the rest of the home's electric energy), and no emissions from on-site solar PV.

Figure 8. Customer economics of limited decarbonization package for retrofit of a single-family home[88]

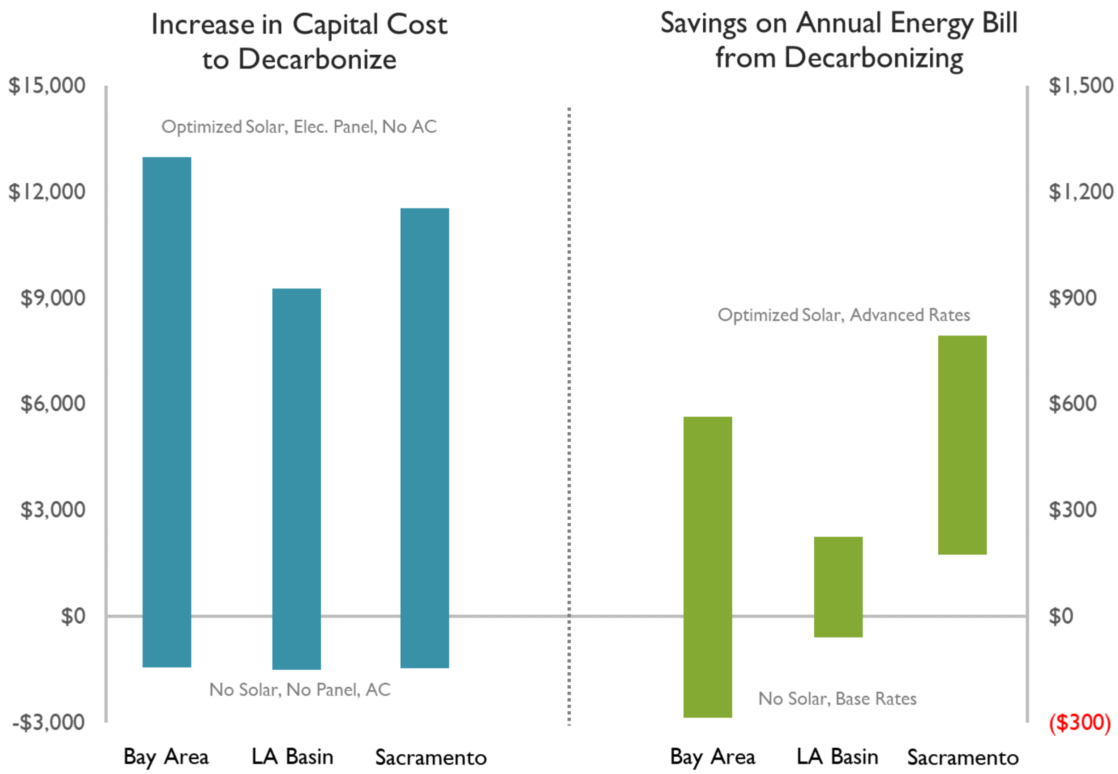


Table 6. Range of net lifecycle costs from decarbonizing in retrofit single family homes. Negative values reflect lifecycle savings.

	Net lifecycle cost			
	Full value for AC; No panel cost	No value for AC	Panel upgrade required	No value for AC; Panel upgrade required
Bay Area	-$3,910 to $2,033	-$910 to $5,033	$761 to $6,704	$3,761 to $9,704
LA Basin	-$1,281 to -$789	$1,719 to $2,211	$3,390 to $3,882	$6,390 to $6,882
Sacramento	-$7,272 to -$4,730	-$4,272 to -$1,730	-$2601 to -$59	$399 to $2,941

Without solar PV, GHG emission reductions from retrofitting with efficient water heating and space conditioning range from 34 to 41 percent; with optimized PV sizing they range from 60 to 69 percent.

88 In each figure, "AC" indicates the home's AC was due for replacement so the installation of a heat pump also delivers that value, while "No AC" means the home sees no value from a new AC.

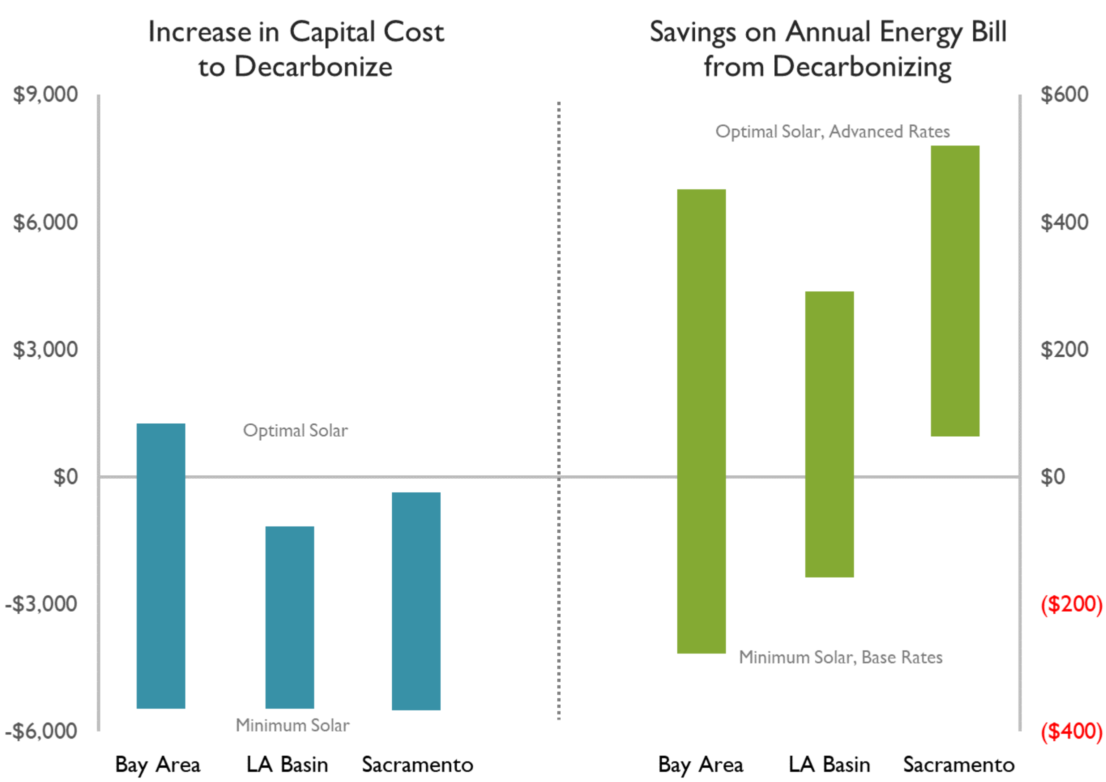
Table 7. GHG emission reductions from retrofitting single-family homes with electric space and water heat, with and without PV. Ranges span the Base and Advanced cases.

	No PV	Optimal PV
Bay Area	40%	60% - 69%
LA Basin	34% - 35%	64% - 65%
Sacramento	38% - 41%	62% - 67%

New single family

The 2019 California Building Energy Code requires that new single-family construction include solar PV. For a new home, all-electric construction provides substantial savings. The cost of optimizing solar PV to minimize electric bills in the electric home is, on average, compensated by savings in gas piping. Homes that choose only the minimal required solar PV are less expensive up front, but see less operating benefit from all-electric construction. The all-electric homes with optimized PV offer hundreds of dollars in annual operating cost savings across all three regions.

Figure 9. Customer economics of decarbonization through full electrification of a new single-family home



Customer lifecycle cost differences between gas and low-emission homes over 20 years, taking into account both upfront capital and operating cost differences, span a range between net benefits from $2,000 and $8,400. On average across climate zones, savings are greater in homes using advanced rates and optimized solar PV.

Table 8. Range of net lifecycle costs from decarbonizing in new single family homes. Negative values reflect lifecycle savings.

	Net lifecycle cost
Bay Area	-$6,591 to -$2,006
LA Basin	-$4,802 to -$3,461
Sacramento	-$8,431 to -$2,250

With minimal solar PV, GHG emission reductions from choosing all electric new construction range from 47 to 58 percent; with optimized PV sizing they range from 60 to 76 percent.

Table 9. GHG emission reductions from new all-electric single-family homes, with minimum (code required) PV or optimal (larger) PV. Ranges span the Base and Advanced cases.

	Min. PV	Optimal PV
Bay Area	47% - 55%	60% - 76%
LA Basin	56% - 58%	67% - 72%
Sacramento	50% - 52%	65%

Multifamily retrofit with CARE rates

Similar to the single-family case, the change in capital cost for electrifying space and water heating in a multi-family unit depends on whether an electrical panel upgrade is required, whether the home was in need of new air conditioner, and how much solar PV is added to power the new electric loads. With CARE rates for both electricity and gas, combined with lower overall energy demand, the net operating cost impact of decarbonizing multifamily housing is smaller than for single-family homes. The net results are shaped by the how the CARE rate discounts for gas and electricity are designed and implemented in each utility pair.

Customer lifecycle cost differences between gas and low-emission homes over 20 years, taking into account both upfront capital and operating cost differences, range between a net cost of $7,600 and net benefit of $4,800. On average across climate zones, savings are greater in more efficient homes using advanced rates and optimized solar PV. As in the single family case, upfront capital costs have a substantial effect on lifecycle costs: Net benefits are greatest if a home benefits from the simultaneous cooling system replacement that comes with heat pump installation ("full value for AC") and does not require an electrical panel upgrade.

Figure 10. Customer economics of limited decarbonization package for retrofit of one unit of a multi-family home

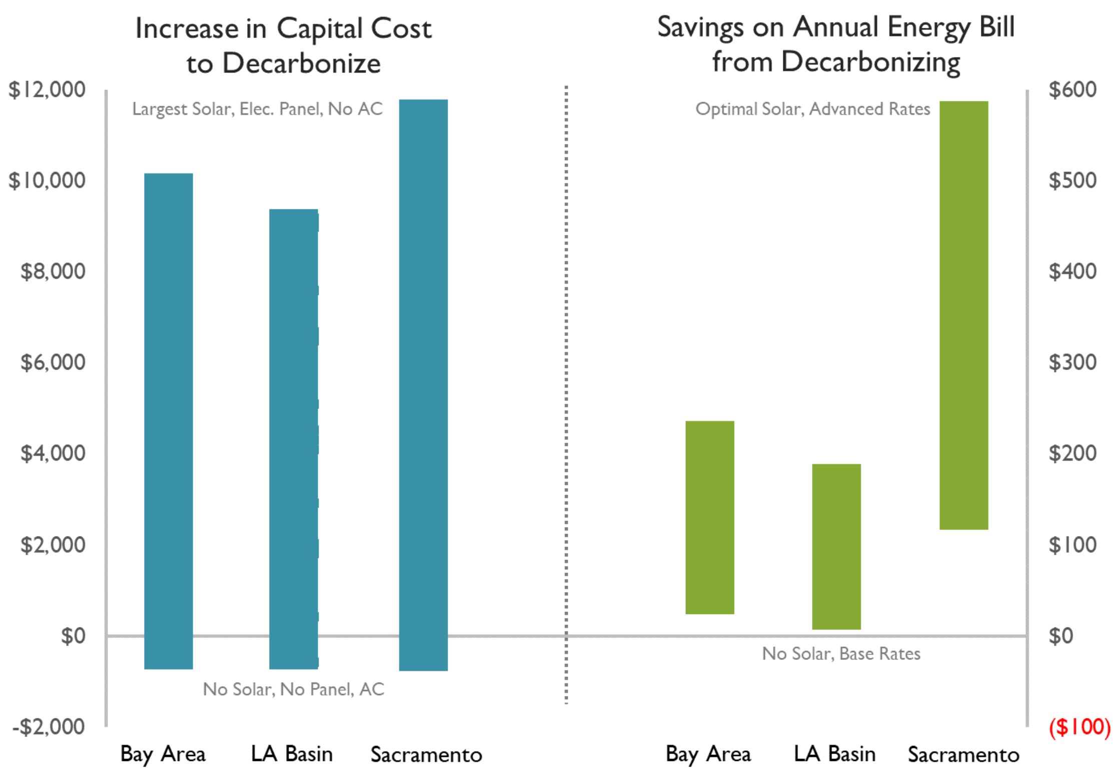


Table 10. Range of net lifecycle costs from decarbonizing in retrofit multi-family homes. Negative values reflect lifecycle savings.

	Net lifecycle cost			
	Full value for AC; No panel cost	No value for AC	Panel upgrade required	No value for AC; Panel upgrade required
Bay Area	-$1,152 to $65	$1,348 to $2,565	$3,519 to $4,736	$6,019 to $7,236
LA Basin	-$757 to $464	$1,743 to $2,964	$3,914 to $5,135	$6,414 to $7,635
Sacramento	-$4,809 to -$1,231	-$2,309 to $1,269	-$138 to $3,440	$2,362 to $5,940

Without solar PV, GHG emission reductions from retrofitting multi-family homes with efficient water heating and space conditioning range from 31 to 41 percent; with optimized PV sizing they range from 57 to 64 percent.

Table 11. GHG emission reductions from retrofitting multi-family homes with electric space and water heat, with and without PV. Ranges span the Base and Advanced cases.

	No PV	Optimal PV
Bay Area	31% - 32%	57% - 61%
LA Basin	31%	61% - 63%
Sacramento	32% - 41%	57% - 64%

Multifamily new construction with CARE rates

New construction sees upfront capital savings, partly a result of not piping for gas. These savings can be more than offset by additional solar PV, which in turn offers increased operating cost savings. Optimal solar PV brings annual operating cost savings from all-electric construction to $200 or more across all three regions.

Customer lifecycle cost differences between gas and low-emission homes over 20 years, taking into account both upfront capital and operating cost differences, range between net benefits of $5,500 and net cost of $340. On average across climate zones, savings are greater in homes using advanced rates and optimized solar PV.

Figure 11. Customer economics of decarbonization through full electrification of a new multi-family home

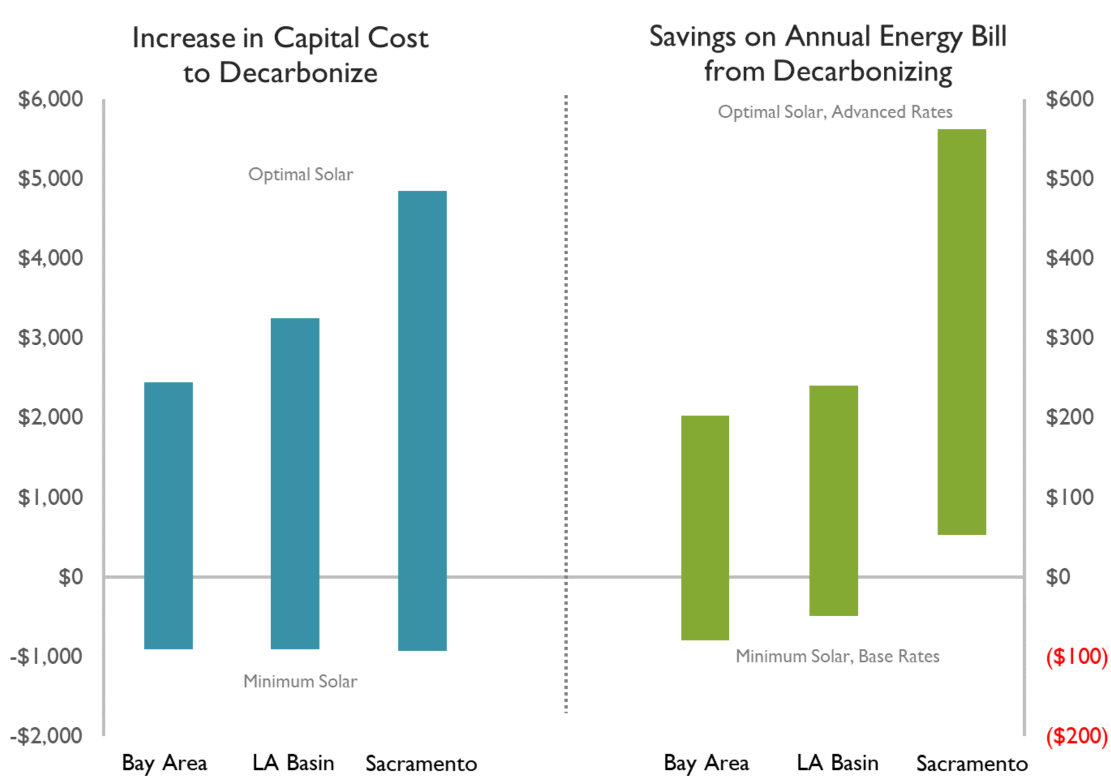


Table 12. Range of net lifecycle costs from decarbonizing in new multi-family homes. Negative values reflect lifecycle savings.

	Net lifecycle cost
Bay Area	-$262 to $127
LA Basin	-$669 to $339
Sacramento	-$5,496 to -$497

With minimal solar PV, GHG emission reductions from choosing all electric multi-family new construction range from 44 to 55 percent; with optimized PV sizing they range from 61 to 73 percent.

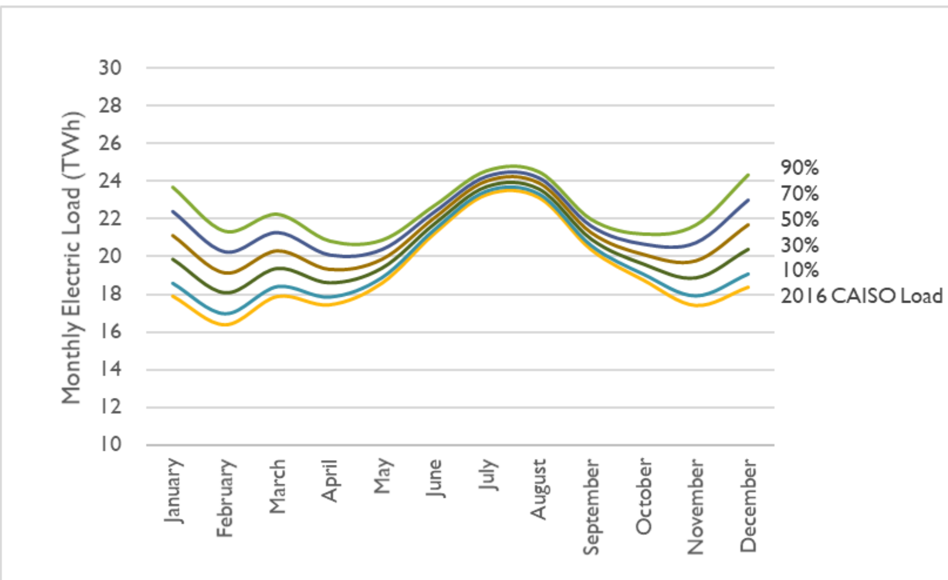
Table 13. GHG emission reductions from new all-electric single-family homes, with minimum (code required) PV or optimal (larger) PV. Ranges span the Base and Advanced cases.

	Min. PV	Optimal PV
Bay Area	46% - 54%	62% - 70%
LA Basin	53% - 55%	69% - 73%
Sacramento	49% - 50%	61% - 65%

6. GRID AND UTILITY IMPACTS

Nearly 80 percent of natural gas in California's residential and commercial sectors is used for water or space heating. Converting these end-uses to electricity that is generated increasingly from renewables like solar and wind could substantially reduce emissions in California's building sector but will necessarily increase electricity consumption across the state. If all water heating and space heating were converted from natural gas to heat pumps, and no complementary efficiency measures implemented, California's electricity use would be expected to increase by approximately 19 percent while gas use would be reduced by a third from today's levels. However, the majority of this additional electricity consumption would occur during the winter months due to the seasonal nature of heating demand. The figure below shows how California's 2016 monthly energy consumption would be expected to change as heat pump penetrations for space and water heating increase from current levels up to a hypothetical penetration of 90 percent.

Figure 12. Projected changes in California annual energy consumption under various electrification percentages, absent complementary energy efficiency and electrification of other sectors



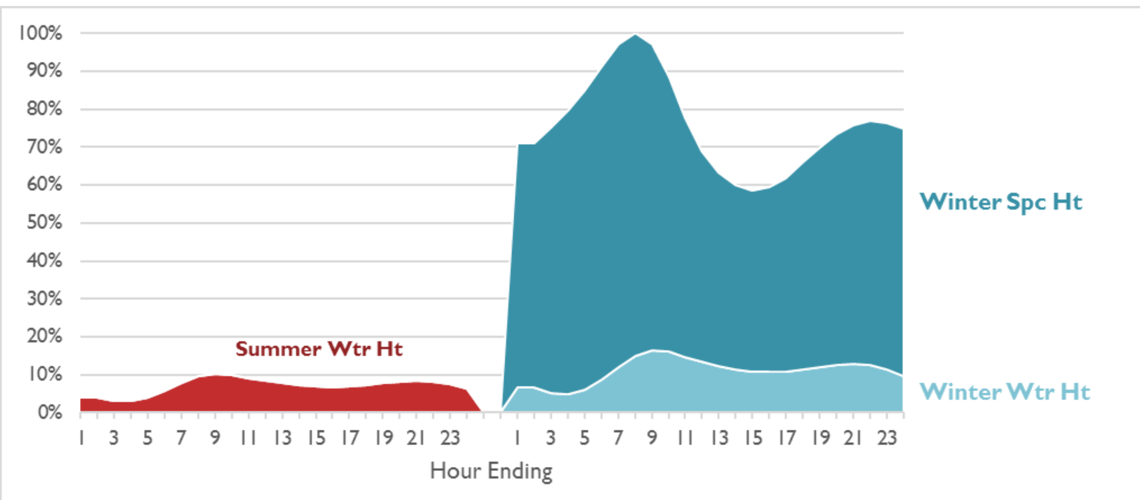
Source: Synapse analysis based on CAISO, EIA, and EPRI data

The impacts on the grid from this increase in electricity consumption are highly dependent on the timing of the demand. If electrification results in greater electricity consumption during peak hours, it could exacerbate existing grid constraints and require additional generation and delivery infrastructure. Additional peak demand could also increase electric sector emissions as fossil fueled resource rise to meet the peak. On the other hand, if the additional load is concentrated during off-peak hours, it would more efficiently utilize existing grid infrastructure and could absorb energy during periods of surplus generation, thereby reducing system costs, and putting downward pressure on electricity rates for all customers.[89]

6.1. End-Use Load Shapes

To determine the grid impacts of electrifying water and space heating, we first analyzed the general usage patterns for electric water and space heat in the residential and commercial sectors using end-use load shapes from the Electric Power Research Institute (EPRI).[90] During the summer months, electrification will result in relatively minor additional load from water heating, but very little additional load from space heating. The graphs below depict the expected hourly load shapes from water and space heating on a peak summer day and a peak winter day (normalized to the maximum combined demand, which occurs in the winter). The graphs indicate that water heating load is highest during the middle of the day for commercial establishments, while residential water heating load tends to peak during the morning and late evening hours. During the winter months, space heating adds additional load for both residential and commercial buildings, particularly during the morning hours. In addition, winter water heating load is higher than in summer due to the additional energy required to heat water when both water and air temperatures are cold.

Figure 13. Residential space and water heating: Peak summer and winter day end-use load profiles

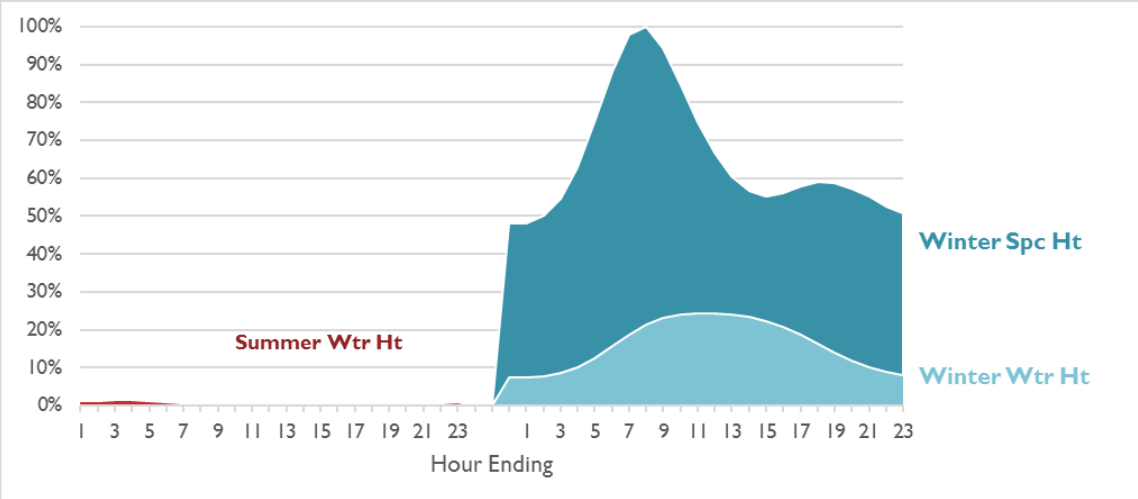


Source: EPRI Load Profiles, http://loadshape.epri.com/enduse.

89 The electricity grid is sized to serve annual peak demand. During other hours of the year, the grid has idle capacity that could be used to serve additional electricity load. By increasing electricity consumption during off-peak hours, volume of energy is increased, but the fixed costs to serve load do not necessarily increase. Thus, the fixed costs of the grid can be spread over a greater number of hours, resulting in lower electricity rates.

90 http://loadshape.epri.com/enduse.

Figure 14. Commercial space and water heating: Peak summer and winter day end-use load profiles



Source: EPRI Load Profiles, http://loadshape.epri.com/enduse.

End-use load flexibility

The load shapes above provide an indication of when electric water and space heating will likely draw energy from the grid without load management. However, a portion of this load could be shifted to other hours without compromising customer comfort if customers are encouraged to do so through time-of-use rates or load management programs. Because of their thermal storage capacity, water heaters have the ability to store energy for later use, essentially operating as a thermal battery. By pre-heating water during hours when demand on the grid is low, electric load can be shifted from peak hours to off-peak hours.[91] In California, this could mean shifting electricity demand from the evening hours to the midday hours when plenty of clean, low-cost solar energy is available.

The figure below illustrates how such peak shaving could work by shifting electricity consumption away from the late evening peak during the summer to the middle of the day when excess solar capacity is on the grid. The resultant load curve is shown by the dotted line. On an individual level, each heat pump water heater shifts relatively small amounts of load away from the evening peak (estimated to be between 0.3 kW and 0.6 kW), but in aggregate the impacts can be quite large.[92]

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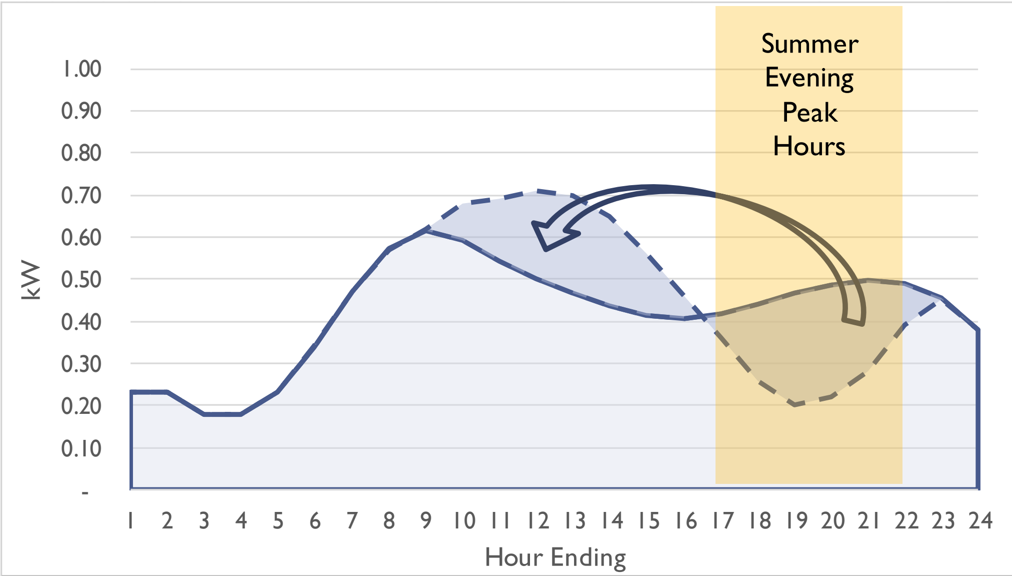
[91] Jim Lazar, *Teaching the "Duck" to Fly*, Second Edition (Montpelier, VT: Regulatory Assistance Project, 2016), http://www.raponline.org/document/download/id/7956.

[92] Pierre Delforge and Joe Vukovich, "Can HPWH Teach the California Duck to Fly?", ACEEE 2018, March 20, 2018

Figure 15. Illustrative summer day potential load shifting for residential water heating



To some degree, homes and businesses can be pre-heated in order to shift space heating load off of peak hours as well. This strategy is most effective in efficient buildings with significant thermal inertia, and can easily be implemented with smart thermostats. Another option that may become increasingly available to customers is the use on-site battery storage to shift grid consumption to off-peak hours. As time-of-use rates become more widespread in California, we expect the prevalence of on-site storage to increase, particularly for customers with rooftop solar. These customers can use batteries to store energy for export to the grid during the evening peak hours. Finally, when confronted with higher on-peak prices, many customers may simply choose to alter their energy usage patterns. This has shown to be an effective strategy for managing electric vehicle load, with approximately 90 percent of charging on EV-only time-of-use rates occurring off-peak.[93]

6.2. Generation and Transmission Impacts

Today, electric energy demand in California peaks during the summer months, resulting in generation and transmission capacity generally being most constrained during these periods. The California Independent System Operator (CAISO) reports that in 2016 California reached its maximum electric demand on a hot July afternoon, with demand peaking between 4 and 5 pm at approximately 46,000 MW. During the winter, electric load tends to be much lower, with demand peaking in 2016 below 35,000 MW during the early evening hours.

These peak load patterns can be expected to shift as water and space heating becomes increasingly electrified. To determine the potential impacts of electrification on peak demand, we applied end-use water heating and space heating load profiles (discussed above) to California's system-wide hourly load

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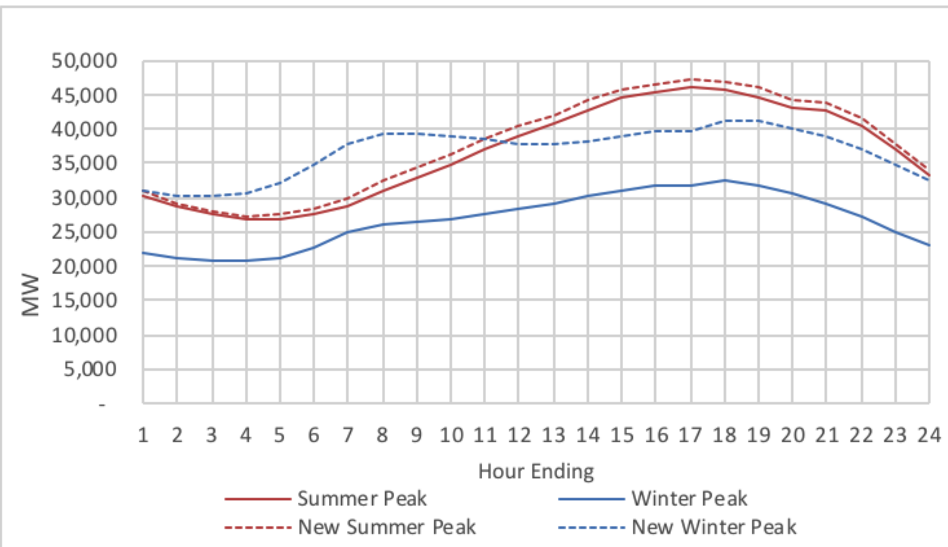
[93] Synapse Analysis of Joint Utilities Load Research Report, Dec 2017.

on summer and winter peak days. These load profiles were scaled based on assumptions regarding penetration levels for heat pump space heating and water heating. This analysis shows that, while electrification of heating and vehicles has the potential to increase peak demand, this effect can be effectively managed through the use of rate design tools and load management technologies previously discussed.

Under a scenario in which 50 percent of the natural gas used for residential and commercial space and water heating is converted to electric heat pumps, California's annual peak demand, which occurs in the summer, could increase by approximately 2 percent, as shown in Figure 16 below.[94] However, this assumes that water and space heating is "unmanaged," that customers do not shift load from peak to off-peak hours, and no complementary energy efficiency. The use of time-of-use pricing or other incentives to shift and reduce demand could reduce this impact substantially, resulting in little to no increase in summer peak demand.

Under this scenario, winter peak demand is expected to increase considerably, due to the substantial additional space heating load. However, on a state-wide level, winter peak demand remains well below summer peak demand.

Figure 16. Impacts on CAISO summer and winter peaks - 50 percent electrification



While energy consumption is projected to increase by approximately 9 percent in the 50 percent electrification scenario, the impacts on system peak demand are expected to be minor, likely less than 1

[94] We assumed a coefficient of performance for ducted heat pumps of 2.0, based on average heating season performance of ducted heat pumps from the Center for Energy and Environment (2018) "Cold-Climate Air-Source Heat Pumps"," available at https://www.mncee.org/resources/resource-center/technical-reports/cold-climate-air-source-heat-pump/, and weather data (TMY3) for California cities. Our analysis also assumed a natural gas furnace annual fuel utilization efficiency level of 79 percent and a gas water heater efficiency factor of 0.6. These efficiency factors were estimated based on DNV GL (2013) 2012 California Lighting and Appliance Saturation Study (CLASS). We assumed a central furnace share of 80 percent and wall and gravity furnace share of 20 percent based on Table 100 of Figure 10, p. 2-18.

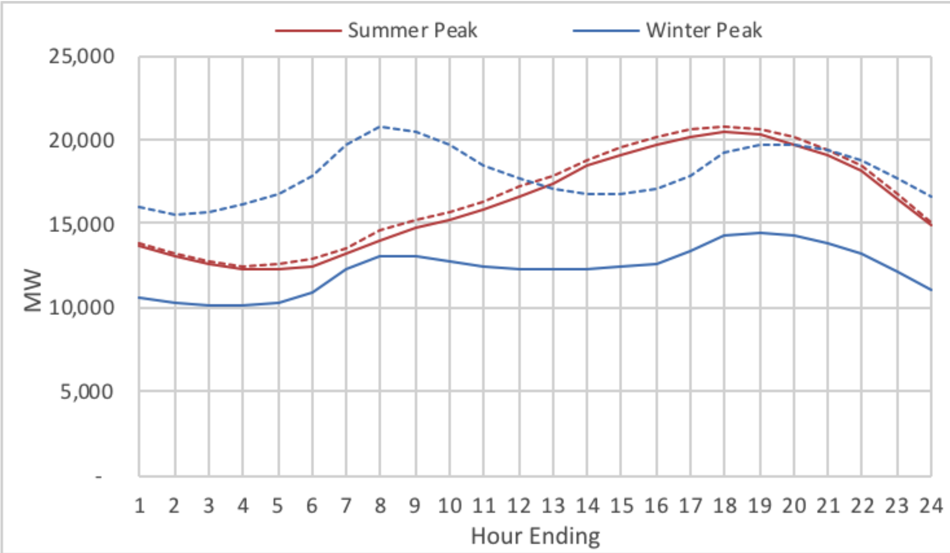
percent (assuming some heat pump water heaters using load management). Further, the efficiency of heat pumps may increase over time, resulting in even lower peak load impacts. The results of this analysis indicate that generation and transmission capacity impacts are likely to be minimal in the near- to mid-term. Winter electricity import and export relationships with generation located in other states could be affected. Policy interventions (including, for example, research and development to improve the efficiency of heat pumps, increased capture of efficiency in other electric applications, innovative electric rate designs that encourage customers to shift load, load management programs, and support for energy storage) can all facilitate the transition to heat pump technologies while mitigating grid impacts. At the same time, the increase in the volume of electricity sales has the potential to reduce electricity rates for all electricity customers by spreading the fixed costs of the grid over more kilowatt-hours.

In the long term, as electrification reaches very high levels, California could require additional generation, transmission, and distribution infrastructure. For example, under a scenario in which conversion of natural gas space heating and water heating to electric heat pumps passes 90 percent, statewide winter peak demand could eclipse summer peak demand (without accounting for energy efficiency or electrification of other sectors, like transportation). Because the transmission and distribution systems have lower losses during cooler weather, however, higher winter peak demand would have little overall impact on delivery infrastructure. Even if the markets for new heating systems transforms rapidly in favor of heat pumps, the natural pace of heating system turnover will allow time to plan for the new loads.

6.3. Local Grid Impacts

Space-heating needs are largely determined by climate, resulting in substantial variation in energy used for space heating across the state. Currently, customers in Northern California, PG&E’s territory, consume the majority of natural gas used for space heating. For this reason, the local impacts of electrification on the transmission and distribution grid are expected to be highest in PG&E’s territory as natural gas space heating is converted to electric heat pumps. Under an “unmanaged” scenario, our analysis indicates that the winter peak load will begin to surpass summer peak load at approximately 50 percent conversion from natural gas to heat pumps, as shown in Figure 17.

Figure 17. PG&E electrification impacts – 50 percent electrification scenario



If PG&E becomes a winter-peaking utility, it is unlikely to require additional generation supply, but could require additional transmission and distribution upgrades to serve load in its territory. In particular, if electrification is concentrated in certain areas more than others, local upgrades to distribution capacity may be required. Again, however, time-of-use rates and load management programs could help mitigate these impacts by shifting load away from peak hours to off-peak hours using storage, pre-heating, efficiency, and other means.

7. CURRENT POLICIES AND POLICY ROADMAP

While California is leading the country on many climate and clean energy policies, it lacks a comprehensive set of policies to achieve a deep decarbonization of the building sector. Several policies even hinder progress toward that goal, although some of those policies are currently being reconsidered. This section identifies and characterizes the relevant existing policy landscape, and then proposes a set of policies and other actions that address market barriers and accelerate building decarbonization.

7.1. Current California Policies

Decarbonization targets and carbon pricing

While California does have explicit economy-wide decarbonization targets, until recently the state had no explicit targets for decarbonization in the building sector. However, in September 2018 the Governor signed into law AB 3232 which requires the Energy Commission to assess how to achieve a 40 percent GHG reduction in the building sector by 2030, below 1990 levels. The implementation of this bill will be critical to determine how to decarbonize California's buildings in a way that benefits customers and the grid.

Apart from AB 3232 and other established policies such as building energy codes and energy efficiency programs, California relies on cap-and-trade, which is designed to let businesses and consumers make the most cost-effective decisions to reduce emissions among a range of strategies. For it to work, however, low emission options must be available and affordable. Right now, clean heating technologies are in a nascent phase in the state and face a host of barriers that a price on carbon won't solve, including lack of awareness and lack of contractor training, and would benefit from further technological improvement.

At $13/metric ton (a typical allowance price during 2015 and 2016, years for which full-year consumption data is available from the U.S. Energy Information Administration),[95] the cap-and-trade program adds about 2 percent (0.3 cents/kWh) to the cost of electricity and 11 percent ($0.07/therm) to the cost of delivered natural gas.[96] Fuel price impacts from cap-and-trade at recent allowance price levels are not sufficient to overcome the market barriers facing nascent clean heating technologies (such as lack of economies of scale, customer awareness, and contractor training). When low-emission heating

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[95] http://calcarbondash.org accessed April 29, 2018.

[96] Synapse calculations based on calendar year 2016 data from the CA ISO (https://www.caiso.com/Documents/GreenhouseGasEmissions-TrackingReport-Dec2017.pdf) and the U.S. EIA (https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_pr_ng.html&sid=CA and https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_pr_es.html&sid=CA)).

options are available and affordable, as they are increasingly today for solar PV and EVs, the fuel price impacts from cap-and-trade will be a more substantial driver for customer adoption.

Senate Bill 1477, also signed in September 2018, will allocate $50 million annually in incentives for very-low emissions new buildings and for advanced clean heating technologies. As with the markets for solar PV and electric vehicles, when the markets for building decarbonization solutions like heat pumps have matured to the point where customers have cost-competitive choices, the need for incentives will sunset and the state can rely more on cap and trade.

Building energy standards

The California Building Energy Efficiency Standards are a powerful set of requirements that establish the market's expectations regarding the state's path forward for building systems throughout the supply chain for building design, engineering, construction, and components. The 2016 Energy Code uses a natural gas baseline for water heating. To design and build a home with electric space and water heating, the builder must show that the new system achieves a lower compliance budget than the natural gas baseline.[97] However, the code's energy cost metric penalizes electric water heating when compared to the gas baseline, even when the electric option reduces GHG emissions. While builders can still choose electric options, the more stringent requirements cost them more in extra efficiency measures, and as a result few choose electric technologies. (Choosing an electric option requires the use of a performance, rather than prescriptive, path to code compliance; additional efficiency measures are required for HPWH installations to meet the code-defined level of performance.) The recently adopted 2019 Energy Code update will remove this barrier in single-family and low-rise multi-family buildings by setting a level playing field between efficient natural gas and electric options: both technologies have prescriptive paths to compliance with appropriate baselines.[98]

Regulated utility efficiency programs

Efficiency programs operated by regulated utilities such as investor-owned utilities (IOUs) and Community Choice Aggregators (CCAs) are shaped by the performance metrics and targets used to evaluate their performance and set shareholder compensation. These programs strongly shape the markets for efficient building products and practices in the state, along with the development of codes and standards. The statutory and regulatory structure for efficiency is built around efficiency being the least-cost resource for each utility, so it should come first in the "loading order" of energy resources.[99]

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[97] See, for example, California Energy Code Subchapter 9 "Low-Rise Residential Buildings – Additions and Alterations to Existing Low-Rise Residential Buildings," Sections 150.2(b)(1)(C) and 150.2(b)(1)(G).

[98] See, for example, the Revised Energy Code Part 6 Chapter 8 at https://efiling.energy.ca.gov/GetDocument.aspx?tn=223257-3.

[99] California Public Utilities Commission, "Order Instituting Rulemaking to Reform the Commission's Energy Efficiency Risk/Reward Incentive Mechanism." Rulemaking 12-01-005. Decision 13-09-023. http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M076/K775/76775903.PDF

In this paradigm, each utility is responsible for efficiency in its own fuel, but no regulated efficiency program takes a total energy, greenhouse gas-based, or fuel neutral, efficiency perspective. There is no framework to reward utilities for fuel switching in service of overall efficiency or decarbonization.[100]

One product of the single-fuel approach to regulated efficiency programs in California is the so-called "three-prong test" that any efficiency program activity that encourages changing fuels must meet. One part of this test requires that the fuel change be cost-effective from a single-fuel perspective and at the measure, rather than portfolio, level.[101] A group of stakeholder organizations has asked the CPUC to revisit the three-prong test[102] in light of the state's decarbonization goals and policymakers' embrace of electrification as a means to achieve those goals.[103] On April 26, 2018, the CPUC agreed to review the three-prong test (but not any broader policy questions about building electrification) over the course of 2018.[104]

Given their single-fuel focus and the three-prong test barrier, it is not surprising that California's regulated efficiency programs offer incentives only for efficient appliances without changing fuel. For example, PG&E offers a $125 rebate for high-efficiency gas storage water heaters, but only if it would be replacing a gas water heater, and $300 toward a heat pump water heater but only if it is replacing an electric water heater.[105]

Municipal utility programs

California's municipal utilities are not restricted by CPUC regulations regarding incentives for fuel switching. Several of them have pushed ahead with electrification incentives in support of decarbonization objectives. For example, the Sacramento Municipal Utility District (SMUD) offers a $5,000 incentive for new homes that are all-electric, and up to $13,750 in rebates for retrofits to all-

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[100] We use the term "fuel switching" in this report to refer to any changes in the fuel used for an end use, whether to or from regulated or unregulated fuels.

[101] See "Commission Should Enable Switching to Clean Energy for Heat" at https://www.nrdc.org/experts/commission-should-enable-switching-clean-energy-heat for more information.

[102] "Motion of the Natural Resources Defense Council (NRDC), Sierra Club, and the California Energy Efficiency Industry Council (The Council) Seeking Review and Modification of the Three-Prong Fuel Substitution Test" filed in Rulemaking 13-11-005 on June 8, 2017. Accessible at http://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M191/K912/191912103.PDF.

[103] See, for example, CPUC President Picker's statement at a February 1, 2017 En Banc hearing: "We can get to 100 percent clean electricity across the state, but we don't get to our greenhouse gas goal unless we start to supplant gas and transportation fuel with clean electricity as our first fuel." (CPUC's En Banc hearing on Community Choice Aggregation (CCA) held February 1, 2017, recording available: http://www.adminmonitor.com/ca/cpuc/en_banc/20170201/ (quoted from Part 2, at minute 19:10).)

[104] CPUC. "Assigned Commissioner and Administrative Law Judge's Ruling and Amended Scoping Memorandum (Regarding Remainder of Phase III)" issued April 26, 2018 in Rulemaking 13-11-005. As of this report's publication, the most recent action in this proceeding is a request for comment issued June 25, 2018.

[105] PG&E. *2018 Residential Rebates Catalog*. Accessed April 29, 2018 at https://www.pge.com/includes/docs/pdfs/shared/saveenergymoney/rebates/ee_residential_rebate_catalog.pdf

electric.[106] SMUD expects the incentive to be cost-neutral for the utility over 13 years: the increased revenue from sales to the all-electric home pays the utility back. Meanwhile, the utility expects that the customer experiences immediate and growing cost savings, and our analysis shows an all-electric new home in Sacramento reduces GHG emissions by at least 67 percent relative to a gas baseline. City of Palo Alto Utilities is piloting heat pump water heater rebates. It is offering larger rebates for those replacing existing gas water heaters: $1,200 rebate when replacing a typical gas water heater, versus $500 when replacing an electric water heater.

These large rebates are needed to jump start this market, which is in its infancy, and over time can be dramatically reduced as the volume of heat pump sales increases and the incremental cost between heat pumps and gas alternatives goes down.

Electric rate design

In addition to the overall level of energy prices, the rates that customers pay have a substantial impact on the overall operating cost. Under the inclining-block rate designs (or "tiered pricing") that have predominated in California in recent years, increased electric consumption has particularly high marginal costs and thus bill impact. These rates have been intended to promote efficiency and conservation. While California utilities offer rates that have larger allowances for baseline consumption in all-electric or electrically-heated homes, inclining block rates can still penalize the customer economics of switching to electric space and water heating.

California's major utilities do now all offer time-of-use rates, but largely with only small differences in rates between time periods. Time-of-use rates with large differences between peak and off-peak prices provide customers with the opportunity to lower bills by shifting usage into low-rate times, while better reflecting the time-dependent nature of electric system costs. Smart thermostats and water heater controls are a key enabling technology for customer savings with these rates. In our customer economics analysis (Section 5), advanced rates with larger differentials improved the economics of low-emission homes when compared with the more widely offered time-of-use rates with small differentials between time periods. The CPUC has set the state on the course to default time-of-use rates by 2019, which should make the customer economics of electrification more positive, and continued progress toward the adoption of load management and larger peak/off-peak differentials will increase these benefits.

California's rate surcharges and riders, such as the public purpose programs and transmission charges, are still designed as flat rates that do not vary in time. These flat adders to time-differentiated rates have the effect of muting the differentials between peak and off-peak times, and the flat design reflects neither marginal costs nor policy objectives.

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[106] https://www.bizjournals.com/sacramento/news/2018/06/28/smud-offering-up-to-13-750-in-rebates-to-convert.html

Technology and market research and development

California is one of very few states with the scale and resources to fund energy and emissions research and development at a scale and pace relevant to the development of technologies and markets to decarbonize buildings, industrial process, and vehicles. The primary state agencies that fund and shape relevant R&D are the California Energy Commission[107] and the California Air Resources Board.[108] State support ranges from basic research in climate science and materials to demonstration projects and development of market-ready products.

State support is far from the only pathway to support R&D in building decarbonization in California. Corporate research on building controls technologies for the “smart home” is underway to meet market demand for new ways to improve home comfort, generate savings, and increase customer satisfaction. In addition, the Electric Power Research Institute, based in Palo Alto, is funded by its member utilities to conduct relevant research for the future of the electric sector.

7.2. Further Actions to Decarbonize California Buildings

Decarbonizing the building sector at the pace and scale necessary to achieve California’s and the world’s 2050 climate and clean air goals will require aggressive market transformation policies. Most buildings last for 50 to 100 years, space and water heating equipment within them for 10 to 20 years. In order to take advantage of natural equipment replacement cycles and minimize costlier mid-cycle replacements, clean heating technologies need to become the default technology by 2030 for most new installations and replacements. This gives California a dozen years to develop the market and to make clean heating technology affordable and accessible to all. This market transformation will require a broad spectrum of policies, that can be placed into four buckets:

1. Raise awareness and educate
2. Set targets and develop plans
3. Remove regulatory and market barriers
4. Transform the market

In this section, we identify actions that Californians can take in each of these areas as part of a coherent suite of actions to reduce building emissions. Lack of coordinated action across all four of these areas will hamper California’s ability to achieve its greenhouse gas goals. We do not address the necessary complementary policies in other sectors. Of these, the most critical is to continue to decarbonize electric supply.

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107 http://www.energy.ca.gov/research/

108 https://www.arb.ca.gov/research/

Raise awareness and educate

One of the biggest barriers to the mass adoption of clean space and water heating technologies is the lack of awareness and understanding of the technology's availability, and of its financial, health, safety, and comfort benefits. Therefore, one of the key policy opportunities is education, outreach, and marketing, addressed to customers, policy makers, product distributors, and the building trades.

Customer and policy maker education on clean heating options

Customers are familiar with the appliances and systems in their homes and commercial buildings, and by default many will simply continue to use those systems and replace them in-kind as they wear out. Changing consumer purchasing behavior is the realm of the applied social sciences: marketing and advertising. A marketing campaign for decarbonized buildings would include:

- education regarding the pros and cons of the various options available to them;
- identifying the selling points for low-carbon options (which may have little or nothing to do with their environmental benefits); and
- communicating the different kinds of benefits available from decarbonized buildings to different audiences (including savings, health, safety, and comfort).

Building industry training and education

Low-emission buildings will necessarily be constructed differently from today's typical buildings. Building practice is implemented by trained professionals, working in ways that align with their experience and expertise, so changes in practice will require training and education throughout the building industry, from architects and engineers to general contractors, plumbers, framers, HVAC specialists, and electricians. Examples of changes that will benefit from training and education include integrated design and construction practices which bring heating and cooling system design and other energy implications into early stages of a building's design, and evaluating the performance of a building during construction to improve real-world performance and change expectations for the responsibility of some building trades for their impact on building performance.

Building industry training on how to build and maintain low-carbon buildings is a promising candidate for public-private partnerships. Such training aligns the interests of the public (emissions reduction and safe and comfortable buildings), the building trades (quality installations with high customer satisfaction), and equipment suppliers (having their products installed correctly in homes and businesses).

Set targets and develop plans

Crafting explicit plans and targets, based on assessment of the potential for deep decarbonization of California buildings, creates market certainty, encourages investment, and provides a framework in which to design other policies or programs (and secure stable funding for those programs).

Develop and adopt targets, with a plan for meeting those targets

The recently passed AB 3232 law sets a tentative target of 40 percent GHG emissions reduction in California's buildings below 1990 levels by 2030 (a level aligned with the state's overall GHG emission limit), and directs the Energy Commission to assess how to achieve it in a manner that is beneficial for consumers and the grid.[109] The resulting work from the CEC will be an opportunity for California to confirm this target and give the CEC and CPUC the statutory and financial means to achieve it.

If California were to adopt this, and post-2030, targets for building decarbonization, it would increase certainty within the markets for technologies and services that would contribute to that goal. This certainty would provide context and direction to the work and practices of architects, engineers, contractors, builders, building performance professionals, and the manufacturers and distributors of electric water and space heating equipment. Tradespeople would know that training in these new technologies would be rewarded with continued demand for their services.

A target should be accompanied by planning about how to accomplish that target. This planning could also include or inform establishing intermediate or sub-targets, such as the expected number of installations of a particular type of equipment by a given date (500,000 controllable heat pump water heaters by some date, for example). Planning would also lay out and coordinate the policies and programs of all sorts that the state, utilities, and others would implement to meet the target (drawing on the kinds of options discussed in the remainder of this chapter). California stakeholders can inform their approach to this planning by building on the state's history with explicit efforts to transform markets through energy efficiency policies and programs. California's electric and gas utilities, as well as CAISO, should also be planning for a decarbonized future.

<u>Examples from elsewhere</u>

California can learn from the process used to develop renewable heating and cooling plans in several northeastern states. California's plan and targets should be specific to the state's particular markets, climate, and policy context, as are each of these other state plans. Massachusetts published its *Commonwealth Accelerated Renewable Thermal Strategy* in 2014,[110] while New York's NYSERDA published its *Renewable Heating and Cooling Policy Framework* in 2017,[111] and Rhode Island its *Rhode Island Renewable Thermal Market Development Strategy* in 2017.[112] Vermont wrapped targets and

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[109] Delforge, P. "Gov. Brown Signs Low-Carbon Buildings Bill AB 3232 into Law" Sept. 13, 2018. https://www.nrdc.org/experts/pierre-delforge/gov-jerry-brown-signs-low-emissions-buildings-bill-law.

[110] Massachusetts Department of Energy Resources. *Commonwealth Accelerated Renewable Thermal Strategy*. Jan. 2014. Available at http://www.mass.gov/eea/docs/doer/renewables/thermal/carts-report.pdf.

[111] New York State Energy Research and Development Authority. *Renewable Heating and Cooling Policy Framework: options to Advance Industry Growth and Markets in New York*. Feb. 7, 2017. Available at https://www.nyserda.ny.gov/-/media/Files/Publications/PPSER/NYSERDA/RHC-Framework.pdf

[112] Rhode Island Department of Energy Resources. *Rhode Island Renewable Thermal Market Development Strategy*. Jan. 2017. Available at:

policies for decarbonizing building heating into its *2016 Comprehensive Energy Plan*.[113] These plans lay out the technology options for decarbonization within the context of each state, generally based on air-source and ground-source heat pumps and modern wood heating. At the same time, each plan reflects the state's particular circumstances, history, and regulatory and market context. They also identify policy paths forward (such as incentives, rate structures, marketing strategies, and workforce development) and set targets for the adoption of different technologies and the associated emission reductions. Vermont, for example, set a target of increasing the fraction of building heating energy use that is renewable to 30 percent by 2025, which could be accomplished by installing heat pumps in 35,000 homes by 2025 and continuing a pace to double the share of building heat that comes from burning wood by 2035.

Remove regulatory and market barriers

Over the past four decades, California's energy efficiency policies have put more emphasis on electric efficiency than on gas efficiency because electric generation was largely fossil-based and one of the largest sources of pollution in the state while gas was generally considered cleaner. With the rapid transition of the electric grid to clean energy sources, the rise of much higher efficiency electric appliances, and a better understanding of the environmental impacts of gas extraction, distribution, and use, efficient electricity use is now clearly understood to be cleaner, but it takes time to update decades of legacy policies to reflect current and projected energy resources, including efficiency potential studies, incentive programs, eligibility and cost-effectiveness requirements for fuel-switching programs, rate design, efficiency targets, and emissions reporting. California has made good progress toward removing these barriers but more work is needed to fully clear the path for the rapid market development of clean heating technology in buildings.

Customers who wish to adopt heat pump space heating and water heating also face a range of market barriers, including lack of capital to afford the upfront cost of new building and water heating systems; lack of access to electric options because distributors and installers do not have the appropriate products in stock for immediate installation upon failure of existing equipment; and signals from regulated efficiency programs that changing fuels is not appropriate or cost-effective.

Rate design for electric space and water heating

The customer economics for building decarbonization that we calculated in Section 5 illustrate that choosing the combination of efficient electric space and water heating technologies has lower upfront costs in new construction and a wide range of net costs (both positive and negative) in retrofit applications, compared with a gas baseline. However, operating costs can be somewhat higher under

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http://www.energy.ri.gov/documents/Efficiency/Rhode%20Island%20Renewable%20Thermal%20Market%20Development%20Strategy%20January%202017.pdf.

[113] Vermont Department of Public Service. *2016 Vermont Comprehensive Energy Plan*. Chapter 7 addresses heat for buildings. Available at https://outside.vermont.gov/sov/webservices/Shared%20Documents/2016CEP_Final.pdf.

current rate structures for customers served by the investor-owned utilities unless the customer is meeting their increased electric needs through net metered solar PV.

The example discussed in Section 5.1, and illustrated throughout Section 5.2, that uses the PG&E electric vehicle rate for an all-electric home illustrates the impact of rate design on customer economics. If decarbonizing homes had access to this, or even more cost-reflective rates, their annual energy bills would be hundreds of dollars less and better reflect the costs these customers are responsible for in the electric system. California utilities and regulators could build from this example to design cost-based "electrification-friendly" that are available, on an opt-in basis, for whole-home use and reflect the marginal costs of delivering energy. Electrification-friendly rates would offer low off-peak rates in the middle of the day and night when wholesale energy prices are low and the grid is not stressed, and higher peak rates in the summer evening and potentially in the winter morning when wholesale prices are high. They could also have lower distribution rates to account for the fact that the customers' share of the distribution system costs is spread over more kilowatt-hours of electricity. Surcharges and riders, such as transmission and public policy charges, can also be updated to time-of-use structures to better reflect costs (e.g., transmission peaks) and advance decarbonization policy.

Cost-reflective electric heating rates would also compensate customers for the grid services provided by controllable water and space heating, such as pre-heating ahead of peak price times and reducing demand during peak periods. Load control can either be done directly by the utility through interactive communications with water heater, or by relying on the customer or the HVAC contractor to program smart thermostats or other local control modules. The electric vehicle rates implemented to date in California have generally taken the latter approach and trusted that electric vehicle drivers can program their cars to charge off peak.

Financial incentives for heat pumps space and water heating

Financial incentives, whether provided through utility programs or by state agencies, can spur market development. For example, the California Solar Initiative drove the state's solar PV market to scale using a system of upfront incentives that declined over time as the market matured. Incentives for heat pumps for space and water heating can mitigate barriers associated with upfront cost, while providing an important signal to the market and to customers that technologies are supported by trusted energy partners. Incentives to distributors and retailers (rather than through customer rebates) can also be tied to the sale of high-efficiency electric equipment. Water heaters, for example, are commonly replaced quickly, on demand, at time of failure. If a local installer cannot quickly access a HPWH from their distributor, a customer may be forced to choose a gas appliance even if the customer would prefer to switch to electric. Incentives can encourage distributors and plumbers to keep HPWHs in stock for use in emergency replacement situations.

The use of ratepayer funds for incentive programs is limited to regulated utilities, and incentive amounts are limited by concerns about keeping rates affordable. California policymakers should therefore consider whether other funding sources, such as cap-and-trade program revenue, are more suitable sources to provide initial public support to building decarbonization. The recently passed SB 1477 provides a promising start: $50 million per year until 2023 from cap-and-trace auction revenue to support two programs.[114] The first, the Building Initiative for Low-Emission Development (BUILD), provides incentives to builders for very-low-emission new buildings using technologies such as heat pumps, solar thermal, and energy efficiency. The second, Technology and Equipment for Clean Heating (TECH) incentivizes distributors and retailers to make low-emission space and water heating equipment available and provides customer and contractor education and training.

Examples from elsewhere

Utilities and state agencies in northeastern states provide incentives for cold climate heat pump deployment.[115] In each state, ratepayer-funded incentives for heat pumps are framed as "market opportunity" incentives: the customer is going to buy a heat pump, so the incentives encourage them to buy the most efficient one. Several states also use other sources of funding, outside of the utility regulatory paradigm, to support fuel switching from fossil fuels (natural gas or delivered fuels) to electricity. The most common source is auction proceeds from the Regional Greenhouse Gas Initiative (RGGI), the nine-state emission allowance program for the electric sector. However, each state that supports heat pumps also uses other funding sources. In Massachusetts, the Massachusetts Clean Energy Center provides incentives funded from its dedicated charge collected on electric bills, while Efficiency Vermont uses RGGI funds combined with revenue from bidding energy efficiency into the regional capacity market.

Eligibility and cost-effectiveness requirements for fuel-switching programs

Electric heat pump and solar thermal options for space and water heating are fundamentally more efficient than combustion options, so electrifying for decarbonization ought to find a comfortable home in energy efficiency. However, as discussed above, the present way that utility program performance is tracked and rewarded incents utilities not to encourage electrification. The CPUC has agreed to revisit the "three-prong test" for eligibility of fuel switching incentive programs during 2018, in light of the state's GHG emissions goals.

If the CPUC does relax prohibitions on fuel switching activities, it will need to establish the parameters for what kinds of activities are appropriately cost-effective. The recent *National Standard Practice Manual* updates the older California Standard Practice Manual to reflect current best practices for developing cost-effectiveness screening tests informed by the state's policy objectives.[116] In concert with screening updates to meet policy objectives, efficiency program targets and metrics for success can also be updated to align with those objectives.

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[114] Borgeson, M. "Governor Signs SB 1477: Delivers Clean Homes to Californians" Sept. 13, 2018. https://www.nrdc.org/experts/merrian-borgeson/governor-delivers-clean-homes-californians

[115] See https://www.veic.org/documents/default-source/resources/reports/veic-heat-pumps-in-the-northeast.pdf for a more complete discussion.

[116] https://nationalefficiencyscreening.org/national-standard-practice-manual/

Transform the market

As barriers to choosing building decarbonization fall, policy can also advance the objective of growing the markets for relevant technologies. Mechanisms to achieve this growth include establishing increasing requirements for these technologies in building codes, further improving technologies, and by integrating their deployment into other policies and programs that apply across all or nearly all California buildings.

Update and align building codes

As discussed in Section 7.1, California's building code shapes the state's construction markets. The 2019 Energy Code update removes a preference for natural gas space and water heat and establishes a level playing field. Future code revisions can encourage the lowest-emission buildings, in a fuel-neutral, performance-based manner that maintains customer choice. Such revisions could include a "zero-emission-ready" requirement that would have the effect of avoiding excessive future infrastructure upgrades when a building owner decides to upgrade to zero-emission building systems.

Support research and development

California has the scale and ability to support research, development, and demonstration of new building decarbonization technologies. The state can tailor its funding to address the most pressing challenges for its own building stock and policies. Based on our market assessments, we believe that some promising areas for R&D could include:

- Increasing efficiency of heat pumps for use in space heating, water heating, air conditioning, and refrigeration;
- Lowering the cost of variable-speed compressors used in heat pumps;
- Developing load management technologies for the diverse array of space and water heating configurations in California's buildings;
- Developing and testing of heat pumps using lower global warming potential refrigerants, including safety analysis of hydrocarbon refrigerants like propane;
- Developing "plug and play" HPWHs that can meet customer expectations while operating off of a standard 110 V outlet;
- Developing more affordable split system water heaters which would increase the number of existing building configurations into which heat pump water heaters can be easily installed; and
- Continued advancement of the building science of indoor environmental quality, ventilation, and moisture management.

In order for customers to feel comfortable adopting a new technology, and for policymakers to feel comfortable supporting that adoption, they need to have credible information about its real-world cost and performance. In the real world, customers set water heaters to different set points, draw water in unique patterns, use their thermostats idiosyncratically, and operate their space and water heating equipment in real buildings, with real ducts, and potentially interacting with other appliances. California policymakers and utilities can draw upon the techniques and best practices developed to evaluate efficient appliances and equipment in the context of regulated efficiency programs.

Couple electrification with efficiency and demand flexibility

When a home or business adopts heat pump or solar thermal technologies for space and water heating, that is also a prime time to consider broader energy efficiency in the building, and vice versa. In particular, heat pumps perform best in reasonably well-sealed and insulated buildings, and duct losses can substantially impair their performance. Thus, encouraging duct improvements, air sealing, and insulation when adopting heat pumps for space heating can provide comfort, performance, and monetary benefits. Even if utility efficiency programs are not engaged directly in fuel switching, they can still harness the opportunity to examine and improve the building. Inverter-based heat pumps, in addition, are very efficient air conditioners, so summer electric savings are intimately paired with fuel switching for the winter.

With California's increasing renewable electricity sources, there is a growing need for grid-responsive load that can help balance variable renewable sources. To that end, the mandate of utility efficiency programs could evolve to include customer-sited demand flexibility. Electrification should include the best cost-effective control technology that will allow grid operators to conduct California's increasingly complex orchestra of distributed energy resources. Developing water heater and smart appliance demand response standards, such as CTA 2045, will facilitate the inclusion of flexible electric heating loads in utility and other electrification programs.

8. CONCLUSION

California has the technical, policy, and regulatory tools at its disposal to substantially reduce GHG emissions from buildings in the state. Heat pumps are the primary technology for a cost-effective pathway to deep decarbonization in this sector because they combine the three essential aspects of building decarbonization: they are very energy efficient, they draw upon an energy source which is low emissions and getting cleaner every day, and they can enhance the flexibility of the grid to both mitigate the impact of their own loads and improve grid operations more generally. Solar hot water can also be a substantial contributor.

California has not yet adopted a comprehensive suite of policies to decarbonize buildings. Even so, it is cost-effective for many buildings to decarbonize through electrification of space and water heating, especially for new construction and when solar PV can be scaled to meet the larger electric load. Further policy development and implementation will be necessary for decarbonization to be cost-effective for all buildings. Policies and programs to decarbonize buildings also include developing state strategies and plans; informing and educating Californians about their options; and harnessing existing policies like utility efficiency programs, building codes, and rate designs.

9. Appendix: Assumptions for Cost and Performance in Customer Economics Calculations

9.1. Space heating and cooling

For each home, we compared the cost to replace a gas furnace and air conditioner with either a new gas furnace and air conditioner or a ducted heat pump. We also compared to the cost for the gas-heated home without a new air conditioner in order to account for homes that either do not have air conditioning or where the AC is relatively new and would not be replaced.

Table 14. Modeled efficiency specifications of heating and cooling equipment

	Heating efficiency	Cooling efficiency
Base	80 AFUE	13 SEER
Advanced	10.5 HSPF	18 SEER

Table 15. Modeled cost of heating and cooling equipment

	SF Retrofit	SF New Const.	MF Retrofit	MF New Const.
Base with AC	$9,628	$7,997	$6,065	$6,065
Base w/ no AC	$6,628	$4,997	$3,565	$3,565
Advanced	$7,342	$6,132	$4,506	$4,506

We based our installed cost figures on analysis conducted by TRC for the City of Palo Alto.[117] We assumed that avoiding AC replacement cost could save $3,000 in single family and $2,500 in multi-family homes. We assumed that a more efficient air conditioner would cost $1,382 more for a 3-ton system in a single-family home and $1,051 more for a 2-ton system in a multifamily home.[118] We assumed that building shells could be improved 14 percent with $1,000 investment in insulation (such as attic batts), and air sealing.

We calibrated energy use to the typical home heating energy use for homes in each climate zone, based on the 2009 Residential Appliance Saturation Survey (RASS). We appreciate the assistance of Meg Waltner of Arup for modeling the performance of Title 24-compliant building shells for new buildings in in each area using CBECC Res. We calibrated the hourly heating energy demand based on typical weather (using "typical meteorological year" data for the San Francisco, Sacramento, and Burbank airports). We also modeled real world performance deviation from specified efficiency for both heat

[117] TRC (2016). *Palo Alto Electrification Final Report*. Available at https://www.cityofpaloalto.org/civicax/filebank/documents/55069.

[118] Based on the incremental costs in the CPUC Database for Energy Efficient Resources (DEER), 2018 version.

pumps and gas furnaces, informed by field efficiency studies.[119] We accounted for the variation in heat pump performance with outdoor weather conditions with a linear fit of declining COP as temperatures fall, calibrated to actual heat pump performance data.

9.2. Water heating

For each home, we compared the cost of either a new gas water heater or a heat pump water heater. We assumed that the gas scenario has a cost of $1,520 to acquire and install an 0.62 UEF gas water heater, with a five percent adjustment for real-world performance. The HPWH scenario, by contrast, would cost $2,500 to install an appliance with a rated UEF of 3.7, and an annual average coefficient of performance of 3.1 to 3.2 (typical of the most efficient available mass market hybrid HPWH in the California climate). We based our installed cost figures on research conducted by NRDC,[120] supported by similar research we conducted directly.

Based on a recent NRDC study, we assumed that adding load management controls to a water heater, allowing it to automatically minimize use during peak priced periods, would reduce the water heater's contribution to electric bills by 10 percent.[121]

We adjusted HPWH energy use to account for the seasons. While HPWHs also dehumidify the area where they are located and can thus displace dehumidifier energy use if placed inside, we did not account for this effect.

Other appliances

For new construction, we modeled an all-electric home which includes induction cooking appliances and heat pump clothes dryers. We assumed a cost of $1,979 for a range with electric induction cooktop,[122] and $956 for a gas range.[123] (Induction cooktops are not likely to be cost effective from an energy efficiency perspective; customers less concerned with cooking performance could save $1,000 or more by choosing a glass ceramic cooktop instead. This would increase the upfront cost savings associated

[119] CEE (2018). "Cold-Climate Air-Source Heat Pumps." Available at http://www.duluthenergydesign.com/Content/Documents/GeneralInfo/PresentationMaterials/2018/Day1/ccASHPs.pdf; Brand et al. (2013) "Improving Gas Furnace Performance: A Field and Laboratory Study at End of Life" U.S. DOE Building Technologies Office. Available at http://www.hvacsave.com/sites/default/files/pdf/gas_furnace_performance.pdf.

[120] Borgeson, M. (April 27, 2018). "Electric Home Study Biased, But Shows CA Wants Clean Energy" https://www.nrdc.org/experts/merrian-borgeson/electric-home-study-biased-shows-ca-wants-clean-energy.

[121] Delforge P, "HPWH Demand Flexibility Study, Preliminary Results", ACEEE Hot Water Forum 2018, https://aceee.org/sites/default/files/pdf/conferences/hwf/2018/2a-delforge.pdf

[122] Mullen-Trento, S., et al. SMUD All-Electric Homes Deep Dive: Final Results. EPRI (2016).

[123] Average of EPRI (2016) and Navigant (2018).

with all-electric homes.) For dryers, we assumed a heat pump dryer with a cost of $1,530[124] and a gas dryer with an installed cost of $600.[125]

9.3. Solar Photovoltaic (PV)

For both new and existing single-family and multi-family homes, we developed costs and production for on-site net metered solar PV that would offset nearly all of the home's electric consumption.[126] (Non-bypassable charges generally prevent annual electric bills from reaching zero.) We assumed an installed cost for solar PV of $3.20/W for retrofit and $3.10 for new construction.[127] For new construction homes, we compared customer economics with a minimal solar PV system (the same size as the system for the gas heated home) and of an optimally-sized larger system. Assumed system capacity ranges from 3.25 kW for a home with gas in the Bay Area using advanced rates to 6.0 kW for an all-electric new home in the Bay Area with base rates, and we assumed a south-facing system.

Table 16. PV capacity (in kW) assumed for each type of single family building and location

	Retrofit Gas Heat	New Gas Heat & New Low Solar	Electric Retrofit	New All Electric
Bay Area: Base	4	3.75	6	5.75
Bay Area: Advanced	3.25	3	4.25	4.25
LA Basin: Base	4.25	4	5	4.75
LA Basin: Advanced	4.25	4	4.75	5.25
Sacramento: Base	4	3.5	5.25	4.75
Sacramento: Advanced	4.5	3.75	5.75	5.25

Table 17. PV capacity (in kW) assumed for each type of multi-family unit and location

	Retrofit Gas Heat	New Gas Heat & New Low Solar	Electric Retrofit	New All Electric
Bay Area: Base	3.25	3.25	4	4.25
Bay Area: Advanced	2.75	2.75	3.5	3.75
LA Basin: Base	3.25	3.25	4	4.5
LA Basin: Advanced	3.5	3.5	4	4.75
Sacramento: Base	3.25	3	3.75	4
Sacramento: Advanced	3.75	3.5	5	5.25

[124] Based on Synapse research of online prices.

[125] Based on Synapse research and Navigant (2018), "The Cost of Residential Appliance Electrification; Phase 1 Report – Existing Single-Family Homes" prepared for the California Building Industry Association.

[126] Systems were sized to leave no accumulated remaining bill credit at the end of 12 months.

[127] Based on pricing at the "Solar for the People" website, https://solar-to-the-people.com/. New construction cost is 3 percent less based on LBNL (2017) *Tracking the Sun*.

9.4. Other costs

In single-family new construction, an all-electric home does not require gas service including piping from the street and plumbing of gas pipes to the kitchen, dryer, water heater, and furnace. This results in a savings of $6,412 compared with a new all-gas home; in a competitive construction market these savings should be passed on to home purchasers.

There is some chance—described in detail in the box in the main text—that pursuing decarbonization in an existing building could trigger electric panel or wiring upgrade costs. While this cost may not always be incurred, we included a cost of $4,671 when developing a range of the upfront costs that a homeowner might face when adopting electric space and water heating.[128]

[128] Panel and wiring upgrade cost based on Navigant (2018).