PATHWAYS TO CARBON NEUTRALITY IN CALIFORNIA

Decarbonizing the Residential Sector

May 2022

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Acronyms, Units, and Chemicals

AC	Air Conditioning / Conditioner
ASHP	Air source heat pump
BTU	British thermal unit
CAPEX	Capital cost
CARB	California Air Resources Board
CEC	California Energy Commission
CFL	Compact fluorescent lamp
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DER	Distributed energy resource
E3	Energy and Environment Economics
EOL	End-of-life
Ft^3	Feet cubed
F-Gas	Fluorinated gas
GHG	Greenhouse gas
GSHP	Ground source heat pump
GWP	Global warming potential
HFC-134A	A type of F-Gas
HFC-1234-yf	A type of F-Gas
Kg	Kilogram
KWh	Kilowatt-hour
Lb	Pound
LEAP	Low Emissions Analysis Platform
LED	Light emitting diode
Lm	Lumen
MACC	Marginal abatement cost curve
MMBtu	Million British Thermal Units
Mt	Million metric tonne
MW	Megawatt
MWh	Megawatt-hour
NEM	Net energy metering
NG	Natural gas
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
RASS	Residential Appliance Saturation Study
RNG	Renewable natural gas
R-410A	A type of F-Gas
Sf	Square feet / Square foot
t	Metric Tonne
T&D	Transmission and Distribution
TXV	Thermostatic expansion valve
VOC	Volatile organic compound
W	Watt
Yr	Year

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Key Findings

- Electrifying water and space heating will be key to decarbonizing the Residential sector.
- Policies aimed at new homes will make marginal improvements (at best) to residential emissions. Achieving emissions goals will require improvements to the existing housing stock.
- Lags due to equipment turnover are important. Models developed for this study show that to reach near net-zero emissions by 2045, 100% of space heater sales will need to be electric by about 2025. Water heater electrification can be delayed slightly. The overall pace of technology investment required -- mainly in space heaters, water heaters, and electric panels -- is quite staggering.
- Water heat pumps are an important opportunity. Water heat pumps have the lowest cost of carbon abatement ($56/t) of all electric technologies evaluated in this study. Water heat pumps are closer in retail price to natural gas (NG) water heaters than space heat pumps are to NG furnaces. In addition, water heat pumps achieve efficiency gains required to return fuel benefits. Water heating is also less peak driven than space heating, and thus the grid can tolerate higher levels of water heating electrification.
- NG furnaces can be swapped with electric resistance furnaces or space heat pumps as near like-for-like replacements. These technologies have distinct pros and cons. Electric resistance furnaces are inexpensive on a capital cost (CAPEX) basis, however significant deployment of electric resistance furnaces would require considerable grid capacity expansion. This is particularly true because space heating is a peak driven service. Space heat pumps have less effect on the grid because they are more efficient. That being said, space heat pumps are more expensive on a CAPEX basis, and they pose substantial risk to increasing fluorinated gas (F-Gas) emissions.
- The state should consider prioritizing space heat pumps in homes that already have air conditioners (ACs) to (partially) offset high capital costs and risk of F-Gas leaks. Due to the dual functionality (provides both heating and cooling services) of heat pumps, future AC and furnace replacement costs can be converted into only one heat pump replacement cost. Furthermore, future AC F-gas leaks can be converted to heat pump F-Gas leaks, as opposed to adding additional refrigerant leaking into the system.
- Investment in heat pumps should ideally be coupled with policies that reduce risk posed by F-Gases. Almost half of the risk can be mitigated by introducing effective programs for responsible end-of-life (EOL) management. In addition, low global warming potential (GWP) refrigerants, such as CO_2, ammonia, and propane, will be needed to reach near net-zero. The state is already investigating low-GWP refrigerators and ACs, and should consider expanding this investigation to space and water heat pumps (which are available overseas).

Introduction

Direct emissions from the Residential sector accounted for roughly 8% of California emissions in 2019 (see Figure 1). In addition, the Residential sector is closely intertwined with many of the other sectors shown in Figure 1. For example, as is shown in Figure 2, California's Residential sector consumed about 33% of electricity in 2019, and thus is arguably responsible for 33% of power plant emissions. The growth of residential photovoltaics (PVs) and onsite battery storage also makes the Residential sector of interest to grid operators and planners, with distributed energy resources (DERs) becoming important drivers of grid operation. Finally, the transportation sector – the largest emitting sector in California's economy – is in some ways inseparable from the Residential sector, with passenger cars being a mainstay of homes across the state, and with rapidly expanding electric car penetration causing increased residential loads.

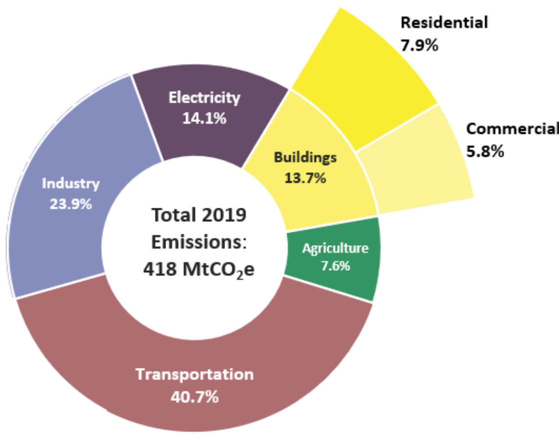

Figure 1: 2019 California emissions (Adapted From 2019 CARB Emissions Data, [1]).

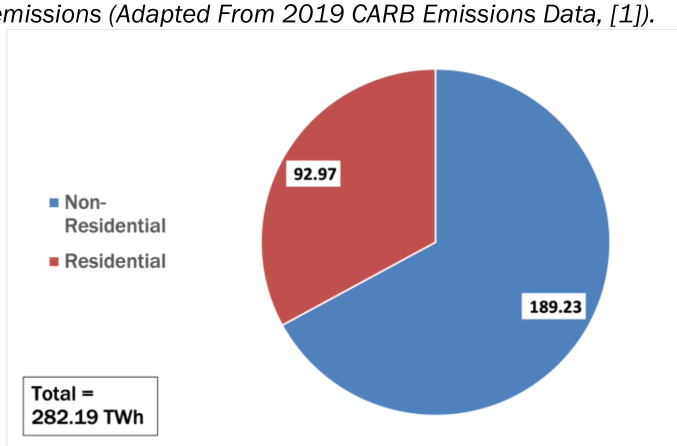

Figure 2: 2019 California electricity demand [2].

The objective of this study is to better understand residential emission sources, as well as the economic / engineering feasibility of decarbonization solutions. To achieve this objective, a bottom-up, stock-and-flow model was developed for the Residential sector. The model, called ResLEAP, was created in the Low Emissions Analysis Platform (LEAP). Reasons for adopting the LEAP model are described in Appendix A. Studies that were influential in development of ResLEAP are discussed in Appendices B and C.

ResLEAP can be used to answer a variety of research questions, including:

Evaluating the Current State

- What are the technologies that contribute most to energy consumption and onsite emissions?
- How do energy consumption and emissions vary geographically across the state?

- How do various electric technologies contribute to the residential load shape?

Scenario Learnings

- Are policies aimed at new homes alone enough to reach 2045 targets?
- What is the sales rate required to electrify all loads by 2045?
- What are the most economically and environmentally efficacious solutions?
- How does the economic and environmental effectiveness of various technologies change with climate zone?
- What is the impact of electric resistance vs heat pump heating on emissions and load shape?
- How important are F-Gases in the face of heat pump growth?

It should be emphasized that ResLEAP is a **load model**. This means that ResLEAP does not explicitly include emissions contributions and spending from offsite power plants, nor does it include the following decarbonization strategies: PVs, energy storage, or demand response. These issues are explored in the companion study "Pathways to Carbon Neutrality in California | Decarbonizing the Electricity Sector" [3], and thus are out of scope for this particular study. Similarly, electric vehicles (EVs) are not covered here, as they are discussed in the companion study "Pathways to Carbon Neutrality in California | Decarbonizing the Transportation Sector" [4]. These areas are indeed important to decarbonizing the Residential sector, however important insights can still be gathered from ResLEAP. Finally, note that results presented here are intermediate, as ResLEAP is under active construction, to eventually be included in a larger model that includes the entire California economy.

Overview of 2019 Emissions and Energy Consumption

The majority of onsite emissions in the Residential sector come from NG combustion for water and space heating. Other significant sources of emissions include propane combustion, refrigerant fugitive emissions, and NG fugitive emissions. The current state of Residential sector emissions and energy consumption is shown in Figures 3, 4, and 5 below. For sake of comparison, estimates from both California Air Resources Board (CARB) [1, 5] and ResLEAP are shown.

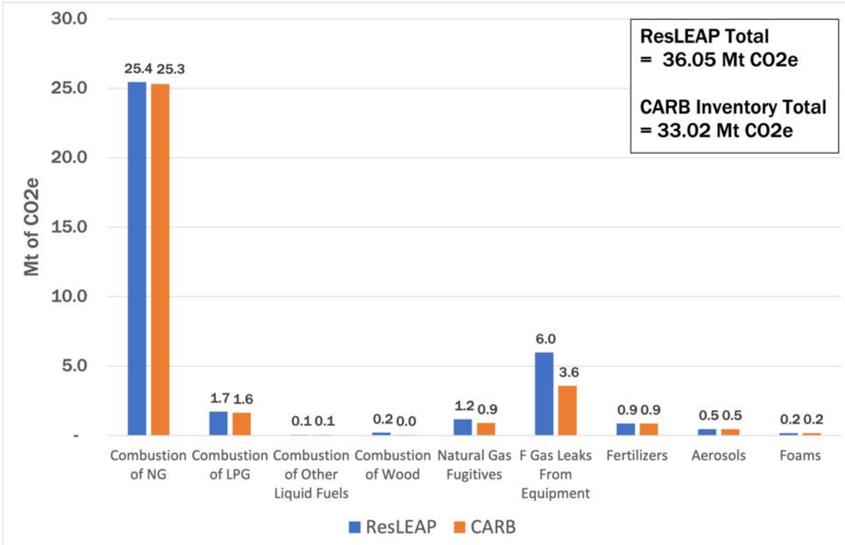

Figure 3: Emissions by End Use, ResLEAP vs CARB (Adapted From 2019 CARB [1]).

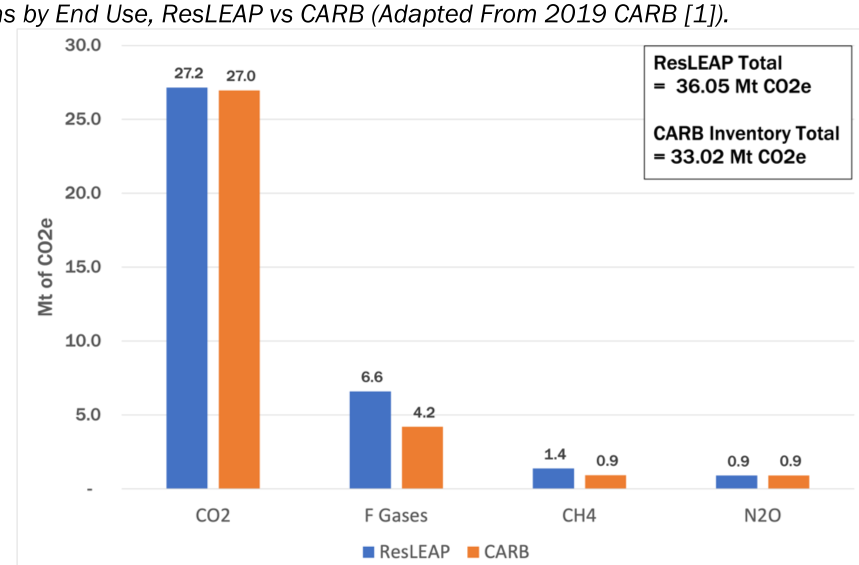

Figure 4: Emissions by GHG, ResLEAP vs CARB (Adapted From 2019 CARB [1]).

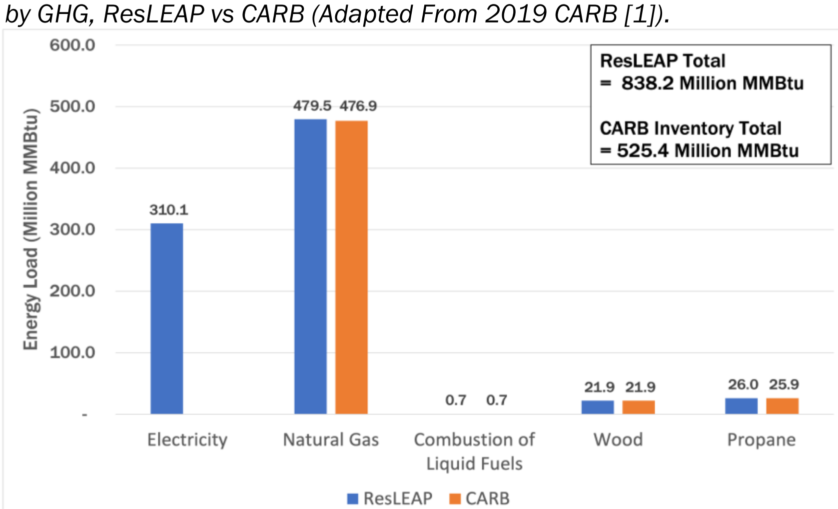

Figure 5: Fuel Activity, ResLEAP vs CARB (Adapted From 2019 CARB [5]).

Figures 3 - 5 illustrate the major sources of emissions and energy consumption in California's Residential sector. Additionally, the figures show that ResLEAP is largely consistent with CARB's emissions and energy consumption estimations. ResLEAP estimates about three additional Mt of CO_2e of emissions in 2019. Most of the difference (2.4 Mt) comes from F-Gas fugitive emissions. The reason for this difference is that ResLEAP adopts bottom-up F-Gas modeling strategies from CARB's F-Gas Inventory Team [6], which includes contributions of both annual and EOL F-Gas leaks. The latter of these sources is less commonly reported, and is not included in the official CARB inventory. However, EOL emissions have been included in some more recent studies, such as E3's residential analysis [7]. EOL F-Gas emissions are an important factor in lifecycle greenhouse gas (GHG) emissions from ACs and heat pumps, and the official inventory would ideally begin to include EOL F-Gas emissions. The other large difference in Figure 5 is that ResLEAP includes electricity consumption. Overall then, beyond intentional differences, results from ResLEAP are very similar to equivalent values from the CARB inventory.

Figures 3 - 5 show that **decarbonizing the Residential sector will largely involve replacing the services currently offered by NG combustion.** NG combustion emissions can be mitigated by 1) electrifying loads, and 2) powering these loads using clean power plants; this general approach will be employed in ResLEAP's scenario modeling.

NG combustion and F-Gas fugitives, the two largest emissions sources, in tandem represent a difficult challenge for engineers and policymakers. NG is in part so widespread because it is a low-cost energy resource -- in this study, electricity is assumed to be about 4.4 times more expensive than NG on an equal energy basis. Efficiency upgrades achieved via heat pumps can partly or completely overcome this price difference. However, a disadvantage of heat pumps is that they use refrigerants, potent GHGs which will become more problematic as homes electrify.

ResLEAP can approximate emissions and energy consumption with geographic specificity. A unique set of 13 climate zones were created, shown in Figure 6. ResLEAP's climate zones originally derive from the 20 climate zones used in the Residential Appliance Saturation Study (RASS), shown in Figure 7. To create Figure 6, individual counties are assigned to RASS climate zones. Notice that in the process, some RASS zones were eliminated; this was done either because 1) RASS did not offer data for that particular zone, and/or 2) said zone is more granular than the county level.

Figure 6: Climate Zones Used in ResLEAP

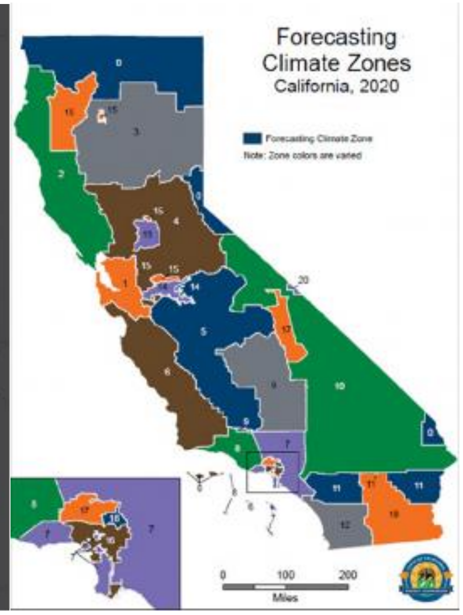

Figure 7: RASS Climate Zones (Adapted From CEC RASS [8]).

Figure 8 maps onsite combustion emissions (27.41 Mt of the original 36.05 Mt), and shows that policymakers could address a significant portion of combustion emissions (nearly half) by focusing first on the Los Angeles & Bay Areas. Additional maps in Appendix D show technology saturations as a function of climate zone.

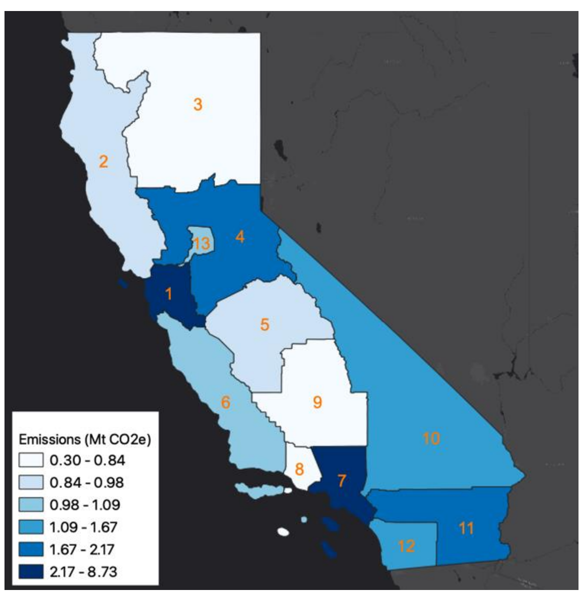

Figure 8: Combustion Emissions by Climate Zone.

Table 1 adds context to Figure 8, showing that emissions per home are similar across climate zone, with variation of approximately -37% to +17% (from the mean). Therefore, climate zones one and seven drive emissions not due to high per capita activity but due to having larger populations. Table 1 also includes information regarding energy consumption (fossil fuel and electricity consumption combined). Geographic trends in emissions and energy consumption are similar.

Climate Zone	Total Combustion Emissions ($Mt\ CO_2e$)	Combustion Emissions Per Home (t CO2e/ Home)	Total Energy Consumption (Million MMBtu)	Energy Consumption Per Home (MMBtu/ Home)
1	4.81	2.15	135.27	60.44
2	0.98	2.07	29.64	62.51
3	0.30	1.27	12.98	55.79
4	2.17	2.16	70.73	70.60
5	0.89	1.85	31.50	65.09
6	1.08	2.18	29.71	60.26
7	8.73	2.00	254.03	58.34
8	0.61	2.26	17.51	64.61
9	0.84	2.05	27.79	68.02
10	1.52	2.34	46.02	70.94
11	1.72	2.23	58.66	76.21
12	1.67	1.48	54.05	48.04
13	1.09	2.00	36.17	66.61
Leftover Propane	0.76	N/A	11.52	N/A
Residual Fuel Oil	0.06	N/A	0.73	N/A
Wood	0.20	N/A	21.88	N/A
Total/ Average	Total = 27.41Mt	Average = 2.00 t/Home	Total = $838.19 * 10^6$ MMBtu	Average = 63.65 MMBtu/Home

Table 1: Combustion Emissions and Energy Consumption by Climate Zone.

Figure 9 shows onsite combustion emissions with granularity by equipment type, demonstrating that the vast majority of onsite combustion emissions are from NG water heaters and space heaters. Therefore, **decarbonizing onsite combustion emissions essentially means decarbonizing NG water heating and space heating**, with other energy services making up a smaller portion of onsite combustion emissions.

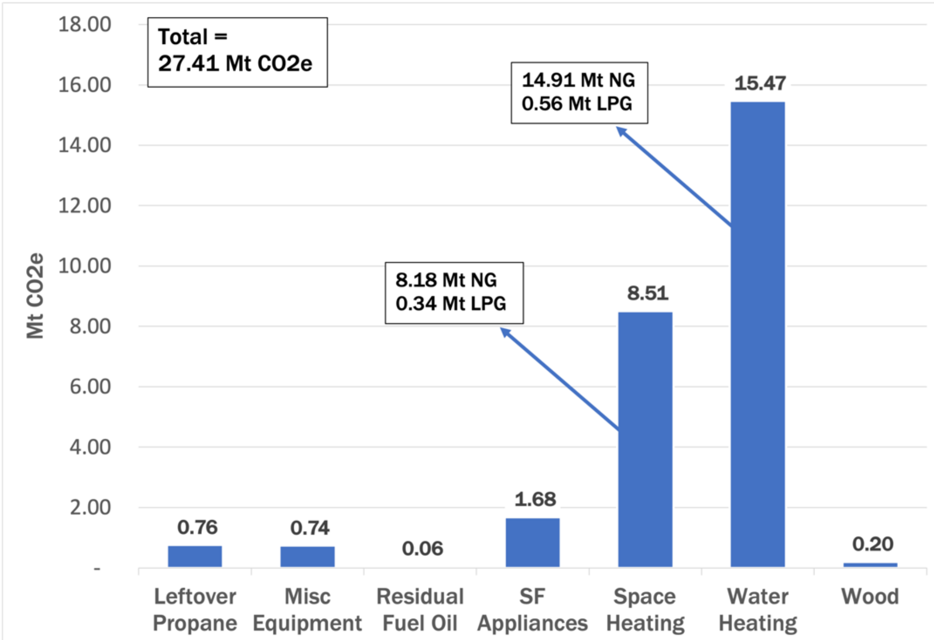

Figure 9: Combustion Emissions by Load Type.

Figure 10 breaks down energy consumption by end technology, organized by electric loads (blue bars) and fossil fuels (red bars). On an energy basis, NG water heating and space heating are still the major drivers, however electric loads are significant, making up 37% of energy demand. Thus, **while NG water heating and space heating are the major drivers of onsite emissions, electric loads are still consequential, demonstrating the importance of a clean grid**.

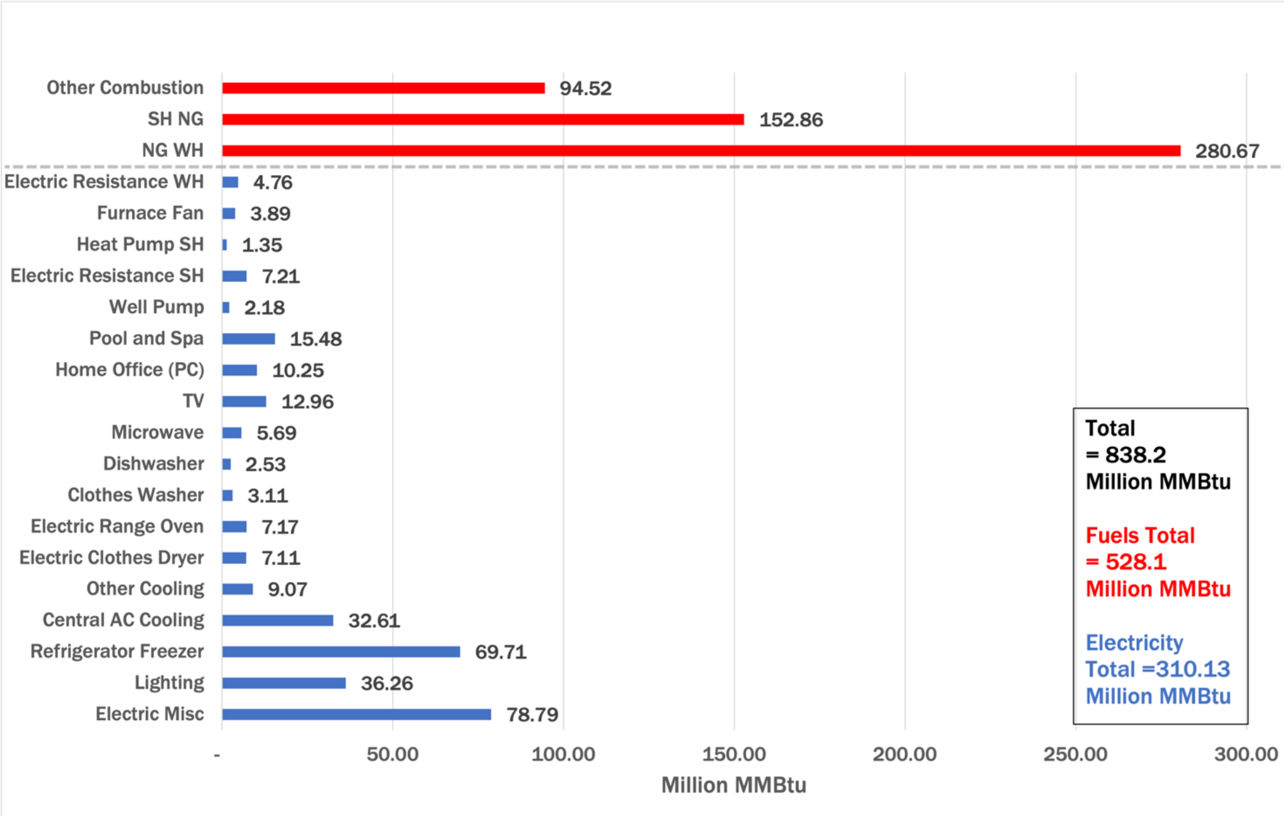

Figure 10: Energy Consumption by End Technology.

The largest driver of electricity usage is a somewhat ambiguous category called Electric Misc. The next largest drivers are refrigerators/freezers, ACs, and lighting. Notice that electric water and space heating are small drivers of electricity use, as these services are predominantly served by NG ; this will be subject to change in future electrification scenarios. Furthermore, while EVs are not covered in this report, EV growth is likely to increase residential load significantly.

In addition to the volume of electricity load, the temporal distribution of electricity load is highly consequential, especially for grid economics. Figure 11 demonstrates the residential load shape using an average day for each month of the year. Figure 11 is also divided by equipment type. In addition, the load shape for California's entire grid (including all sectors of the economy) is shown [9]. Figure 11 shows that the Residential sector and the overall California economy have similar load shapes, which is consistent with other demand-side models [10]. Importantly, while cooling is one of the smaller drivers of overall energy consumption (Figure 10), cooling is highly concentrated in the summer months, and thus is largely responsible for California's summer peak. Note again the absence of water and space heating from Figure 11: this will change upon future electrification.

An important metric is the grid utilization factor, defined in this report as the ratio of actual electricity demand to hypothetical electricity demand if the Residential sector demanded at its peak (21.56 GW) the entire year. Visually, grid utilization can be thought of as the extent to which the residential sector takes up the portion below the dotted line going across Figure 11.

Conceptually, grid utilization is important because the grid must be built to accommodate peak power, and thus earning a higher utilization factor implies greater use of our electricity investments.

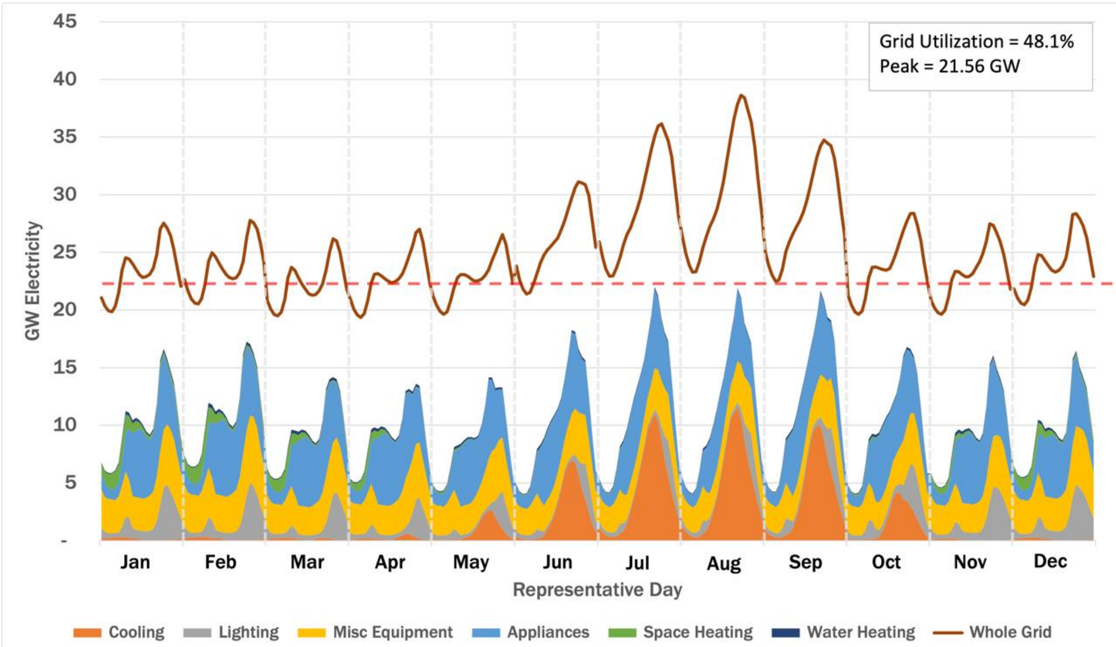

Figure 11: 2019 Residential Load Shape.

In addition to combustion emissions, ResLEAP can also granularly model F-Gas fugitive emissions, as is demonstrated in Figures 12 and 13.

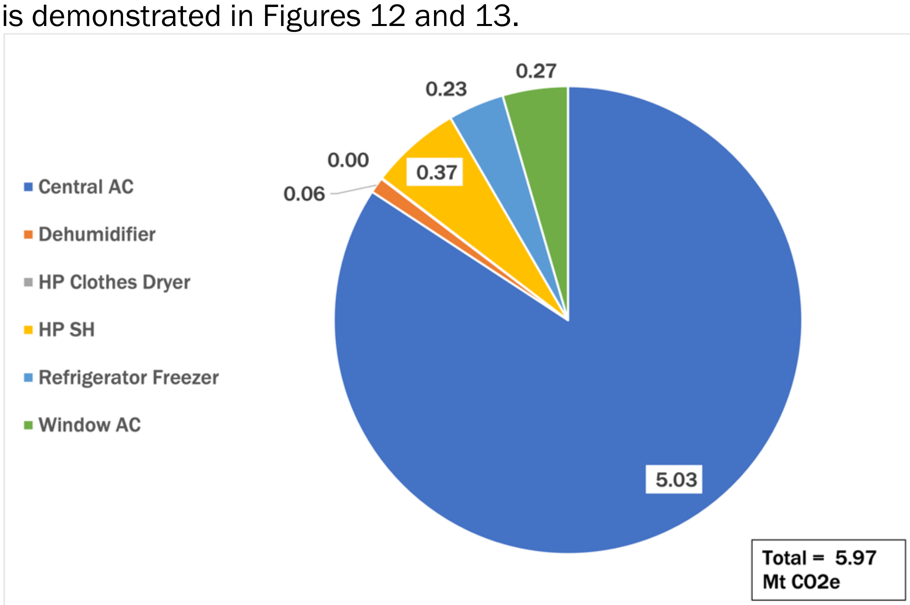

Figure 12: F-Gas Emissions by Equipment Type.

Figure 12 shows that the majority of F-Gas emissions come from AC leaks. It is notable that the next largest contributor is space heat pumps, even though there are much fewer space heat pumps in California than refrigerators -- this is because space heat pumps have a large charge size (amount of F-Gas contained in the system).

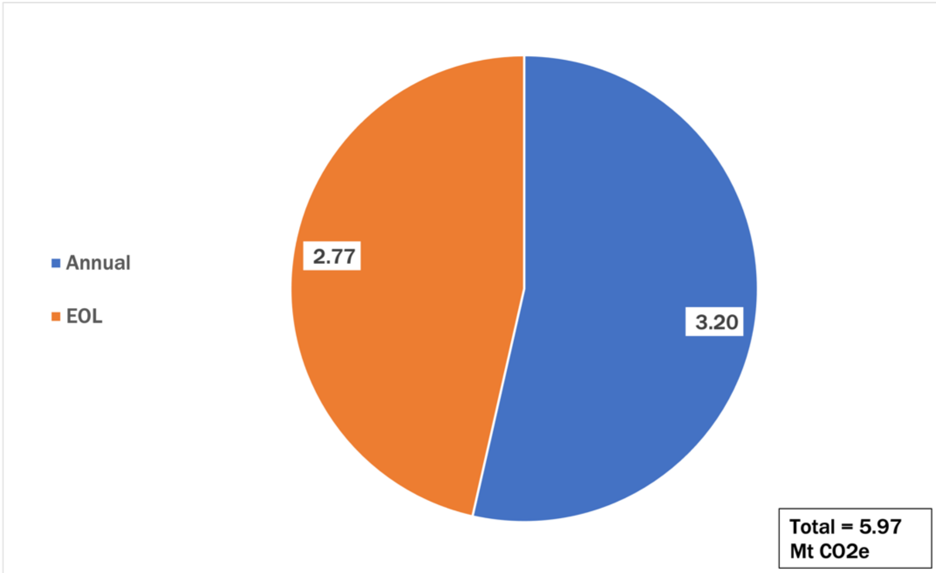

Figure 13: F-Gas Emissions, Annual vs EOL.

Figure 13 shows that F-Gas emissions are somewhat evenly distributed between annual and EOL contributions. EOL emissions refer to emissions upon retirement. CARB's F-Gas Inventory team believes that the majority of F-Gases are vented at EOL [6], leading to significant EOL emissions. Overall, **about half of F-Gas related risk can be mitigated by implementing responsible EOL strategies.**

Decarbonization Opportunities and Challenges

Technologies

Decarbonizing the Residential sector can be done with technologies that replace services currently offered by NG, mainly space and water heating, but also cooking, clothes drying, and other appliances. Technologies can be placed into five categories:

1. Housing efficiency upgrades used to reduce energy service needs
2. Efficient appliances -- equipment that use less fuel for the same service
3. Electrified appliances
4. DERs, mainly solar PV, battery storage, and demand response
5. Experimental technologies that are not yet commercialized

Only categories two and three are explicitly included in ResLEAP.

Category 1: Housing Efficiency Upgrades

Many technologies are available to improve a home's thermal efficiency. Upgrades are typically targeted at HVAC, housing envelopes, and water heating [11]:

- *HVAC*: technologies are available to increase the efficiency of ACs (example: thermo-expansion valves), to reduce the need for ACs (example: smart thermostats and fans), and to improve duct efficiency (example: insulation) [11].

- *Building Envelope:* envelopes are improved by adding insulation to the ceiling, floors and walls, by reducing infiltration, and with window coatings and films [11].
- *Water Heating*: technologies are available to reduce the need for hot water (example: faucet aerators and low-flow showerheads) and to increase the thermal efficiency of storage/delivery systems (example: water heater blankets and pipe wrap) [11].

Upgrades like these, if available, can cost-effectively reduce NG and electricity consumption. These opportunities should especially be pursued amongst older, inefficient homes that have yet to install these retrofits [11]. However, it is possible that many homes have already installed these efficiency upgrades. A refreshed understanding of efficiency upgrades penetration could be useful, with the last robust and granular study done about 10 years ago [12]. In the absence of recent data, housing efficiency upgrades are not currently included in ResLEAP.

Category 2: Efficient Appliances

In addition to making the overall home more efficient to reduce service needs, residents can install efficient appliances that offer the same energy services for less energy input. Tables 2 and 3 below quantitatively describe the technoeconomics of efficient appliances included in ResLEAP. Table 2 offers a quantitative view of the baseline technologies, while Table 3 details the energy intensity of efficient appliances in comparison to the baseline technologies. Note that throughout the report, efficiencies above 100% refer to a technology's coefficient of performance. Appendix E qualitatively describes how the modeled efficient technologies work.

Technology	Current Stock Saturation [2]	Assumed Efficiency [3]	Weighted Average Installed Cost ($/Unit) [2, 4]	Maintenance Cost ($/Unit/Yr) [2]	Lifetimes (Yr) [2]
Stock Indoor Lighting	100%	32.2 Lm/W [5]	N/A	N/A	5
Baseline Natural Gas Furnace	76.2%	80.0%	$6,283	$40	22
Baseline Electric Resistance Furnace	15.23%	98.0%	$5,315	$40	23
Baseline Air Source Space Heat Pump	3.71%	252.0%	$15,478	$72.5	16
Baseline NG Water Heater	84.32%	63.0%	$2,269	$0	13

2 Residential Appliance Saturation Study (RASS) [8]

3 Updated Buildings Sector Appliance and Equipment Costs and Efficiencies [13]

4 E3's Residential Building Electrification study [7, 14]

5 Baseline lighting efficiency is calculated as a weighted average based on lighting efficiency metrics [15] and best available lighting stock data [12]

Baseline Electric Resistance Water Heater	5.83%	93.0%	$2,935	$0	13
Baseline NG Range / Oven	73.07%	19.3% [6]	$980	$0	12
Baseline Electric Range / Oven	46.26%	N/A	$2,041	$0	12
Baseline Electric Clothes Dryer	32.22%	3.74 lb/kWh	$2,041	$0	13
Baseline NG Clothes Dryer	44.30%	3.32 lb/kWh	$1,010	$0	13
Baseline Central AC	60.18%	422.0%	$12,422	$72.5	18
Baseline Room AC	15.90%	351.7%	$813	$0	10
Baseline First Refrigerator	100.00%	389 kWh /yr	$983	$10	17
Baseline Second Refrigerator	28.76%	489 kWh/yr	$1,468	$25	17
Baseline Freezer	18.28%	297 kWh/yr	$655	$5	22
Clothes Washer	80.5%	2.05 ft^3 / kWh / cycle	$989	$10	12
Dishwasher	68.0%	125 kWh / yr	$584	$0	15

Table 2: Baseline technologies snapshot.

Technology	**% of Energy Used Compared to Baseline Tech**	**Weighted Average Installed Cost ($ / Unit)**	**Maintenance Cost ($/Unit/Yr)**	**Lifetime (Yr)**
Efficient Indoor Lighting	48.0% [7]	N/A	N/A	5
Efficient NG Furnace	81.0%	$7,317	$40	22
Efficient NG Water Heater	78.0%	$3,152	$0	13
Efficient NG Clothes Dryer	95.0%	$1,197	$0	13

[6] Baseline NG Range/Oven efficiency is calculated using an energy based weighted average between cooktops and ovens

[7] Lighting efficiency improvement compares average efficiency of LED and CFL bulbs [15] to stock bulbs

Efficient NG Range/Oven	91.0%	$1,016	$0	12
Efficient Central AC	87.0%	$13,972	$72.5	18
Efficient Room AC	96.0%	$898	$0	10
Efficient First Refrigerator	92.0%	$1,154	$10	17
Efficient Second Refrigerator	98.0%	$1,521	$25	17
Efficient Freezer	93.0%	$708	$5	22
Efficient Clothes Washer	71.0%	$1,509	$10	12
Efficient Dishwasher	69.0%	$676	$0	15

Table 3: Efficient technologies snapshot.

Category 3: Electric Appliances

Electrification of heating can largely be achieved with two families of technologies: electric resistance heating and heat pump heating.

Resistance Heating

Resistance heating involves converting electricity directly into radiant heat. Electric resistance technologies are generally more efficient than their NG counterparts, however efficiency gains are typically not enough to overcome the increased cost of electricity compared to NG. That said, electric resistance technologies generally have a lower installed cost than heat pump technologies, which might be attractive to some consumers. Electric resistance heating options are available for both space and water heating.

Electric resistance space heaters include radiators, baseboard heaters, and electric resistance furnaces [16]. The lattermost is nearly a like-for-like replacement with NG furnaces, as heat is generated in a central location and then ducted throughout the home. Electric resistance space heaters operate near 100% efficiency.

Electric resistance storage water heaters are nearly like-for-like replacements with NG storage water heaters, in that water is heated in a central location, stored, and then piped throughout the home. Electric resistance storage water heaters operate at 90% - 100 % efficiency, and also show great promise to act as a thermal battery [16].

Heat Pump Heating

Heat pumps work by moving heat (via the vapor-compression cycle) rather than by generating heat. For this reason, heat pumps can achieve well above 100% efficiency, up to 400% or more in some cases [13] [8]. Efficiency improvements from heat pumps can sometimes be enough to overcome the increased cost of electricity compared to NG. Heat pumps, however, have a higher installed cost than electric resistance devices. In addition, heat pumps employ high-GWP refrigerants, which can leak to the environment and cause warming (unless carefully managed). Heat pumps are available for both space and water heating; several configurations for each are listed in Appendix E.

It is notable that space heat pumps can work in two directions, offering both heating and cooling services (a space heat pump operating in reverse is an AC). This dual functionality increases the economic viability and environmental benefits of space heat pumps [7, 16]. By comparison, water heat pumps only offer one energy service, as city water is piped directly into the home to satisfy cool water needs. Below are some market barriers and opportunities for space and water heat pumps.

	Market Barriers	Market Opportunities
Heat Pumps	• Technology is unfamiliar to customers and installers • Most consumers tend to replace heating systems with the same kind they installed previously, especially when replacing upon failure and under time pressure • Few utilities have heat pump programs / incentives • Customers can expect to benefit marginally or suffer a net cost, especially when electric rates are high compared to gas rates, and/or if rate design is not optimized for electrification. • Installing heat pumps could trigger expensive electric panel upgrades, especially in older homes or if the home does not already have AC installed • Water heat pumps produce hot water at a slower rate than NG or electric resistance options, sometimes resulting in a worse user experience. • Water heat pumps substantially cool the air that surrounds them, which should be accounted for when purchasing and installing the devices.	• Heat pumps are more economically favorable for new construction or large retrofits • Heat pumps are more economically favorable in homes that can completely avoid gas pipeline installs or service upgrades (all-electric homes) • Heat pumps are more economically favorable when electric panel upgrades are not needed • Some utilities offer incentives • Pairing with home efficiency upgrades can improve economics • Heat pumps are more favorable in areas where electricity rates are relatively low compared to gas rates

Table 4: Space & water heat pumps, market barriers & opportunities (Adapted From Hopkins et al. [16]).

Solar Water Heating

In addition to electric resistance and heat pump technologies, water heating can be achieved via solar heating. Solar water heaters should be thought of as pre-heaters to gas or electric storage units. Solar water heater panels, typically installed on the roof, are essentially weather-proofed boxes that are made of materials to maximize solar absorption (such as glazing). Fluid traverses through the boxes and is heated to high temperatures. This is in contrast to solar PV panels, which convert solar rays to electrons; in fact, the process of converting solar rays to heat

[8] It should be noted that heat pump efficiency is a function of outside air temperature, especially for heat pumps that are stationed outside and directly exposed to weather. Geographic and seasonal variations in heat pump efficiency are not captured in ResLEAP.

is more efficient than the process of converting solar rays to electrons. In general, solar water heaters are more expensive than electric resistance or heat pump water heaters, however they mitigate F-Gas leaks and are beneficial from a resources management perspective. Different types of solar water heater configurations are described in Appendix E. Table 5 lists some market barriers and opportunities for solar water heaters.

	Market Barriers	**Market Opportunities**
Solar Water Heater	• High upfront capital costs • Permitting costs and requirements • Lack of knowledge of solar water heaters amongst consumers • Lack of developed workforce	• The most promising market for solar water heaters is commercial applications, particularly businesses that use large amounts of hot water (lodging, health, restaurants). • There are existing incentives via the CSI Thermal Incentive Program

Table 5: Solar water heaters, market barriers and opportunities (Adapted From Hopkins et al. [16]).

Cooking and Clothes Drying

Space heating and water heating are responsible for the majority of residential NG end use, however, two additional technologies that contribute to NG consumption are range ovens and clothes dryers. For the prior, electric options include electric resistance cooking, induction cooking, and convection ovens. For the latter, customers can choose between electric resistance and heat pump dryers. The workings of these technologies are described in Appendix E. Due to constraints in the data sources used, only electric resistance clothes drying and cooking options are included in ResLEAP. Table 6 lists some market barriers for electric range ovens and clothes dryers.

	Market Barriers
Induction Cooktops and Ranges	• Consumer bias or preference for gas cooking, especially with cooking being something of an art to many • Cost compared to gas alternative • Requires magnetic cookware (pots and pans made of steel or iron) • Magnetic field can interfere with digital thermometers
Convection Ovens	• Cost compared to gas alternative • Users may have to adjust recipes to account for differences in cooking time
Heat Pump Dryers	• Cost compared to gas or electric resistance clothes dryers • Many customers and contractors are unfamiliar with the technology because it has only been available in the US for a few years • Increased drying time

Table 6: Electrified ovens and clothes dryers, market barriers (Adapted From Hopkins et al. [16]).

Mirroring Tables 2 and 3, Table 7 quantitatively describes the technoeconomics of electric appliances included in ResLEAP

Technology	% of Energy Used Compared to NG Alternative	Weighted Average Installed Cost ($/Unit)	Maintenance Cost ($/Unit/Yr)	Lifetime (Yr)
Electric Resistance Furnace	82%	$5,135	$40	23
Space Heat Pump	32%	$15,478	$72.50	16
Electric Resistance Water Heater	68%	$2,935	$0	13
Solar Water Heater (Gas Backup)	23%	$12,785	$25	23
Solar Water Heater (Electric Backup)	23%	$13,662	$25	23
Water Heat Pump	19%	$4,061	$20	13
Electric Clothes Dryer	89%	$2,041	$0	13
Electric Range/Oven	N/A [9]	$2,041	$0	12

Table 7: Electric technologies snapshot.

Box 1

Panel Upgrades

Homes must be built to meet the maximum level of coincident current demanded by all electric appliances. Residential electric panels are typically built to handle 60 amps (A), 100 A, or 200 A. A panel size of 60 A will likely be insufficient to accommodate electrified space and water heating. For example, water heat pumps are expected to add about 11.25 A - 22.5 A to existing current loads. Space heat pumps may add up to 20 A depending on whether the home already has central AC. 200 A panels will easily accommodate electrified space & water heating, as well as EV charging. Panel upgrades can cost up to $4,000 [16] [10].

Figures 14 and 15 emphasize space heating and water heating technoeconomics. The figures illustrate that incumbent NG technologies are generally amongst the least efficient, cheapest options. By comparison, heat pump and solar heating technologies achieve well above 100% efficiency, however at higher upfront cost.

[9] Electric efficiencies are not provided [13], and thus RASS survey data is used directly

[10] In line with E3's assumptions, panel upgrade costs are included for homes built in 1978 and prior [14] (this is done using a weighted average). Panel costs aren't included for new construction homes, because they are assumed to be included in the general cost of constructing the home.

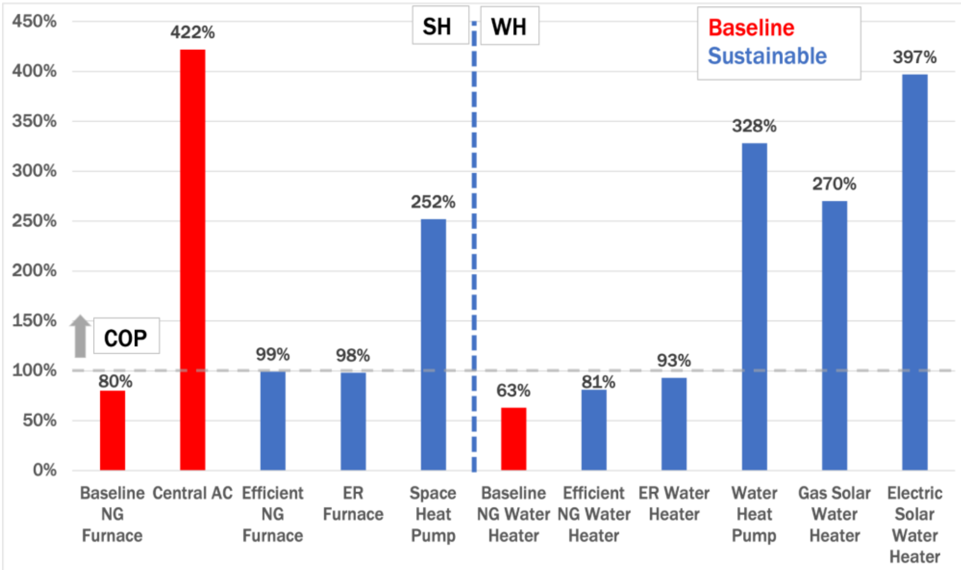

Figure 14: Efficiency of space/water conditioning technologies.

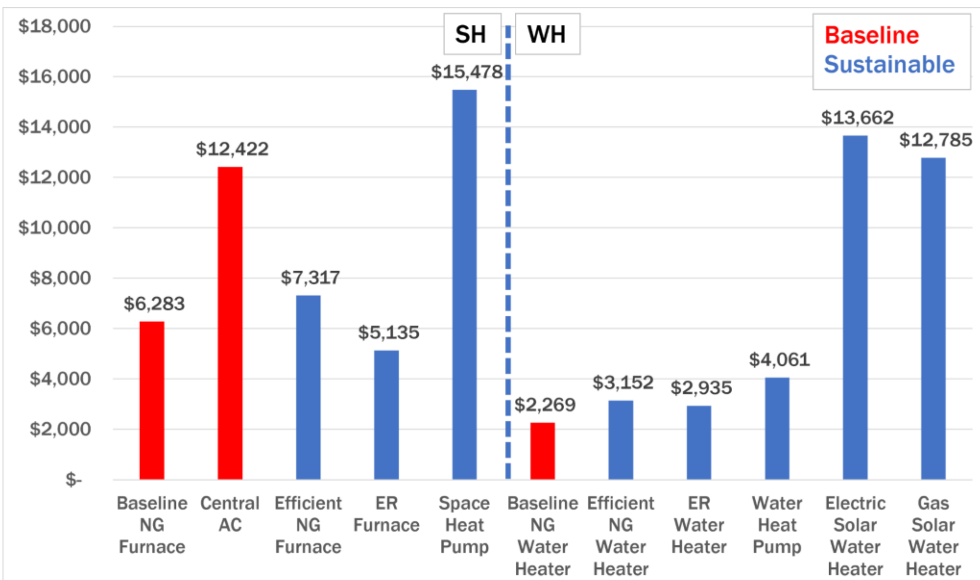

Figure 15: Installed cost of space/water conditioning technologies.

Figure 16 shows the expected efficiency gain of each electric appliance, defined as the ratio of electric appliance efficiency to the efficiency of stock NG devices [11]. The horizontal line across Figure 16 equals the ratio of electricity cost to NG cost on an equal energy basis. Fuel savings are expected when efficiency gains exceed the electricity price premium, or in other words, when efficiency improvements are enough to overcome the increased cost of electricity [12]. Figure 16 shows that **water heating options present an opportunity for residents to save money on fuel costs.** Water heaters perform better than space heaters both because electrified water heaters are more efficient than electrified space heaters (Figure 14), but also because stock

[11] Stock appliances refers to those appliances that are currently in homes today.

[12] The exception is solar water heater with gas backup, which always generates fuel savings

water heaters are less efficient than stock space heaters (63% for NG water heaters vs 80% for NG furnaces).

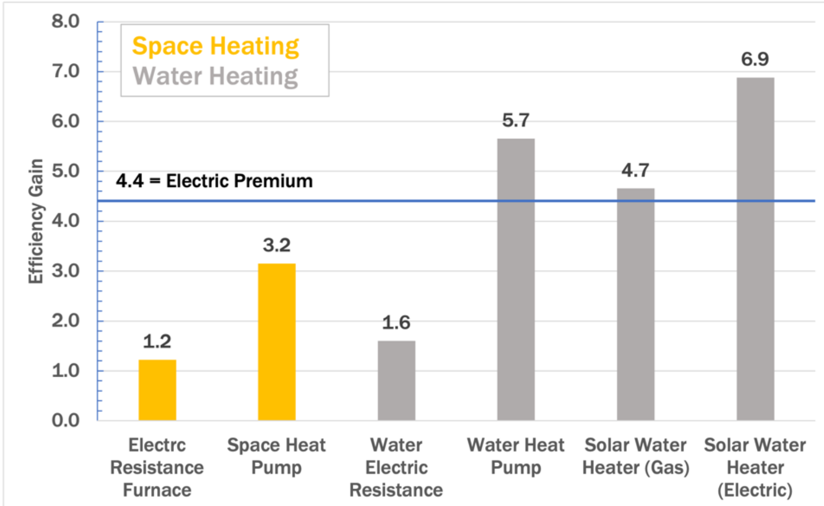

Figure 16: Electric technologies efficiency gain.

Figure 17 shows the equipment lifetime of various appliances. Equipment lifetime dictates the speed in which electrification sales will need to be ramped up to reach net zero by 2045. For example, NG water heaters have a shorter lifetime than NG furnaces, and thus it may be possible to delay water heating electrification slightly while still achieving full electrification by 2045. Equipment lifetimes also contribute to economic performance – for example, solar water heaters benefit economically from being more durable than the baseline, in that fewer replacement sales are required over time.

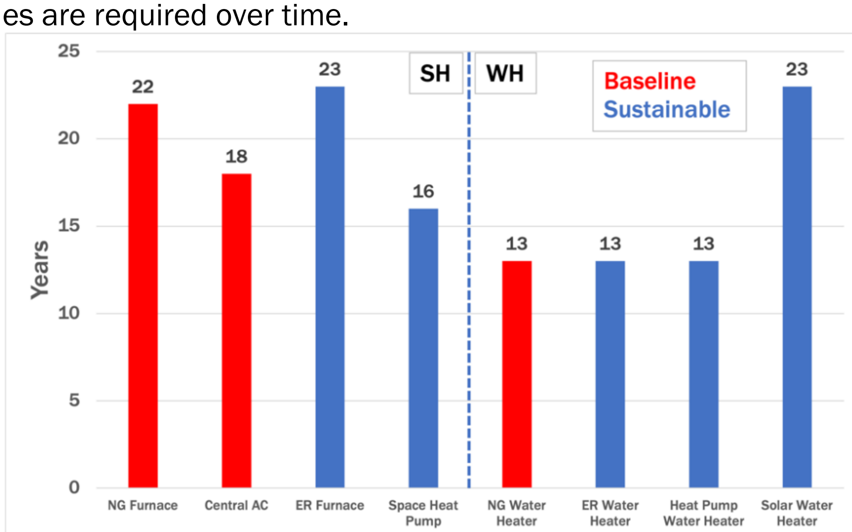

Figure 17: Equipment lifetimes.

Table 8 summarizes the proclivity of refrigerant-based technologies to leak F-Gases into the environment. As a point of comparison, NG furnaces and NG water heaters annually produce (on average) 814.4 and 1355.6 kg CO_2e/Unit/Yr from combustion (respectively). F-Gas leaks from space heat pumps can be partially mitigated by scrapping AC units. Overall, F-Gas emissions are significant enough to be considered when making policy choices. However, F-Gas emissions are of less concern for water heat pumps and refrigerators, mainly because these technologies have smaller charge sizes (they require less F-Gas to run properly).

Equipment	Annual Emissions [kg CO_2e/Unit/Yr]	EOL Emissions [kg CO_2e/Retired Unit/Yr]
Space Heat Pump	426.7	5,416.9
Water Heat Pump	19.2	1,646.4
Central AC	362.6	4,930.9
Refrigerator	2.5	167.3

Table 8: F-Gas emissions potential by technology (Adapted from CARB F-Gas Inventory Team [6])

Box 2

Low-GWP Heat Pumps

According to this analysis, low GWP heat pumps will be something of a breakthrough in the effort to decarbonize. **Low GWP space heat pumps –** mainly using ammonia, propane, HFO1234-yf, or CO_2 **– are now either available for commercial application or are under active development by manufacturers.** In addition, **water heat pumps utilizing CO_2 are already commercially available in the US** -- a Japanese company called Maekawa produces a commercial sized unit, whereas a US company called Saden USA produces a residential size unit. In fact, the use of CO_2 offers better performance, with CO_2 water heat pumps operating at higher efficiency in a wider outdoor temperature range and without the need for electric resistance backup (thereby reducing contribution to electric panel amperage), while also producing hotter water. However, **due to limited economies of scale and technical constraints, these technologies are currently twice as expensive as standard water heat pumps. CARB is already investigating low-GWP options for refrigerators and ACs, and should consider expanding these efforts to space and water heat pumps** [16].

Category 4: Distributed Energy Resources

This category of technologies includes solar PVs, batteries, and demand response systems. These technologies are not yet reflected in ResLEAP, which is a demand side model only. This section briefly describes the current state of residential solar PV, as well as its economic and environmental efficacy.

A significant feature of the 2019 Title 24 standards is a requirement for new homes to be built with solar PV systems (with limited exemptions). While battery storage is not yet obligatory, it can be used -- along with demand response technologies -- to decrease PV size requirements [17] .

About 3,414 MW of residential solar has already been installed in California, along with 1,608 MWh of battery storage [18] [13]. If all new single-family homes are built with a median sized PV system (2.7 kW), residential solar capacity could reach about 5,700 MW by 2045. As a means of comparison, California reached 33,309 MW of total solar capacity in 2021 [19], meaning residential solar is and will continue to be a small but noticeable contributor to the overall solar mix.

[13] These values represent raw capacity installed, and may double count installations in which residents replace old solar or battery systems with new ones.

Decreasing module costs, high electricity prices, favorable incentives, and new financing mechanisms can explain the rapid growth of PVs in California. For new homes, the cost of solar can be included in the mortgage; increased mortgage costs are offset by decreasing electricity bills by about $35/month (on average). Alternatively, leasing models can be used to reduce upfront costs sometimes down to $0, while offering up to 20% savings on electricity bills [17]. Leasing models mitigate CAPEX barriers experienced by many low income families, but can introduce new barriers when selling a home. When purchasing PV, the average Californian sees about a six-year payback [20]. While some of PV's economic efficacy can be attributed to decreasing panel costs and creative financing mechanisms, some of it can also be attributed to favorable programs that are subject to change, mainly net energy metering (NEM).

NEM policies define the rate at which California residents are able to sell excess electricity back to the grid, and the rate at which they are charged for demanding electricity from the grid. NEM is oftentimes criticized for being too favorable for homes with PV. This is mainly because residents are able to sell electricity back to the grid at the time-of-use rate. Doing so implies that residents provide the full value represented in the cost of electricity, but in reality residents only offer the value generation and not transmission and distribution (T&D). Furthermore, solar exports to the grid typically happen when power prices are increasingly low (sometimes near-zero), but the home still receives the full value of power. Utilities must ultimately retain value by shifting costs onto all other ratepayers. The net result: electricity prices increase amongst homes without solar PV, which generally tends to be lower income families [21]. Equity concerns have led to further conversation regarding NEM. For example, there are suggestions to reduce generation credits, to be based on the cost avoided by the utility rather than time-of-use rate (the difference partly being in T&D costs). The California Energy Commission (CEC) believes that in a NEM system based on avoided costs, PV cost tests would pass in only five out of 16 climate zones, narrowly failing in all others [17].

An additional criticism of residential PV is that there is no need to produce onsite electrons, when electricity can easily be transmitted from utility PV facilities that are both more efficient (as they are well managed and optimally located) and cheaper (due to economies of scale). Indeed, the CEC states that utility scale solar is about $1.05/watt - $1.20/watt cheaper than residential solar. However, utility sized facilities come with their own host of challenges, including: acquiring and siting large plots of land, building T&D lines and transformer infrastructure, and negative impacts on wildlife. Furthermore residential PV paired with batteries can have innate benefits, including flexibility to offer ancillary services as well as grid reliability during system wide failures [17].

As residential solar continues to grow, California utilities must factor DERs into their grid planning processes. Utilities have concluded that DERs can sometimes provide benefits to the grid, such as by limiting distribution capacity requirements [14]. Conversely, DERs can sometimes have negative impacts, such as 1) loading grid infrastructure beyond safe operational limits, 2) making it more difficult to meet voltage and power quality standards, and 3) decreasing system

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[14] Solar can reduce distribution capacity requirements only if the following conditions are met: 1) the region of interest requires distribution expansion in the first place, 2) enough DER capacity is installed to satisfy transformer peaks, 3) DERs are installed in the correct location, and 4) DERs are controlled and managed to avoid failures.

reliability. Smart home load management can help mitigate these effects. In the end, the consequences of PV on the grid are typically dependent on local conditions [22].

DERs can vastly reduce a home's environmental impact. The CEC provides the following table to demonstrate the emissions reductions potential of DERs. The table summarizes model results for a 2,700 ft^3 home in Sacramento. When the model home upgrades to 2019 efficiency guidelines, emissions are reduced by 3.4 t/yr. Adding solar PV further reduces impact by an additional 0.8 t/yr, due to electric loads being supplied by cleaner electricity. Electrification reduces home emissions by an additional 1.2 t/yr, with the remaining emissions driving from evening and nighttime reliance on thermal power plants. Finally, the home reaches near net-zero by employing battery storage, with solar power being generated during the day and stored for use later.

Fuel	**Home Features**	**Emissions Per Home ($t\ CO_2$/Yr)**
Mixed Fuel (Gas and Electric)	1997 Standards, no PV	6.5
Mixed Fuel (Gas and Electric)	2019 Standard, no PV	3.1
Mixed Fuel (Gas and Electric)	2019 Standards, with 3.1 kW of PV	2.3
All Electric	2019 Standards, with 3.1 kW of PV	1.1
All Electric	2019 Standards, with 3.1 kW of PV, with battery storage	0.2

Table 9: Mitigation Potential of DERs for a 2,700 sf Sacramento Modeled Home (Adapted From CEC [17]).

Overall, DERs such as residential solar and battery storage have great potential to help the state reach net-zero goals, however implementation should be carefully planned to mitigate growing concerns surrounding equity, grid planning, and more.

Category 5: Experimental Technologies

Experimental technologies include those that are not yet commercially available in the US, and/or strategies that are not commonly discussed as decarbonization pathways for California's Residential sector.

Biogas

In lieu of electrification, it is possible to pipe renewable natural gas (RNG) to homes using existing NG pipelines. This strategy is attractive because it requires little to no effort by end consumers, leaving residential decarbonization entirely in the hands of centralized stakeholders. However, RNG is in limited supply, deriving mainly from landfills and anaerobic digesters. Furthermore, converting crops directly into fuel raises land use concerns. RNG is also quite expensive, except if used for transportation in which case Low Carbon Fuel Standard credits can be applied. For these reasons, the scientific community generally suggests prioritizing RNG to sectors of the economy that are more difficult to electrify, such as long-haul transportation, aviation, shipping, combined heat and power plants, and other industrial processes [16].

Hydrogen

It is also possible to satisfy heating and cooling services using hydrogen generators. Japan is leading the world in hydrogen powered communities, currently constructing HARUMI FLAG, an isolated town with a full-scale hydrogen infrastructure system including hydrogen pipelines and residential generators [23]. In total, Japan has already installed 300,000 hydrogen generators. However, hydrogen powered homes face a number of challenges in California, including 1) the high cost of hydrogen compared to NG and electricity, 2) clean hydrogen is still in its infancy, with the majority of hydrogen being produced via steam methane reforming, and 3) expensive infrastructure requirements to store, transport, and deliver hydrogen [24].

Critical to residential hydrogen will be the ability to flow hydrogen through existing NG pipelines. Currently the European Union only allows for 5% hydrogen flow (by volume) through a NG pipeline. The GHRYD project in Northern France is able to inject up to 20% hydrogen [24]. Economically transitioning to hydrogen homes may require 100% hydrogen flow through existing pipelines, which will be challenging due to the permeability of existing pipes and risk of embrittlement. More work needs to be done to explore whether piped H2 can realistically contribute to residential decarbonization in California.

District Heating

District heating involves producing electricity and/or heat in small centralized facilities, and then distributing said commodities via wire/pipeline over scales that range anywhere between a few homes to entire cities. Most district heating today is supplied by fossil fuels (89%), but some is powered by biomass, geothermal, or nuclear. District heating more commonly provides services to commercial complexes such as universities, hospitals, and government buildings. Overall, district heating accounts for only 10% of global heat demand, but is highly prevalent in certain countries. The biggest challenge facing further development of district heating is the infrastructure and system-level changes required for implementation [24]. These challenges can be more easily overcome during the construction of new neighborhoods.

Scenario Analysis

Scenarios in this study can be placed into three categories.

- **Baseline**: business-as-usual case that assumes no policy action
- **Building Blocks Scenarios**: these scenarios test the environmental and economic efficacy of individual technology/policy options.
- **Combined Scenarios**: in these scenarios, building block scenarios are stacked on top of each other to decarbonize the entire Residential sector.

Insights Gained From Baseline Scenario

In the baseline scenario, upon natural retirement, appliances are replaced with the baseline options shown in Table 2. In addition, the growth of new homes is incorporated. Differences between “Old Homes” (that is, homes that were built following less stringent guidelines) and “New Homes” are accounted for in the model.

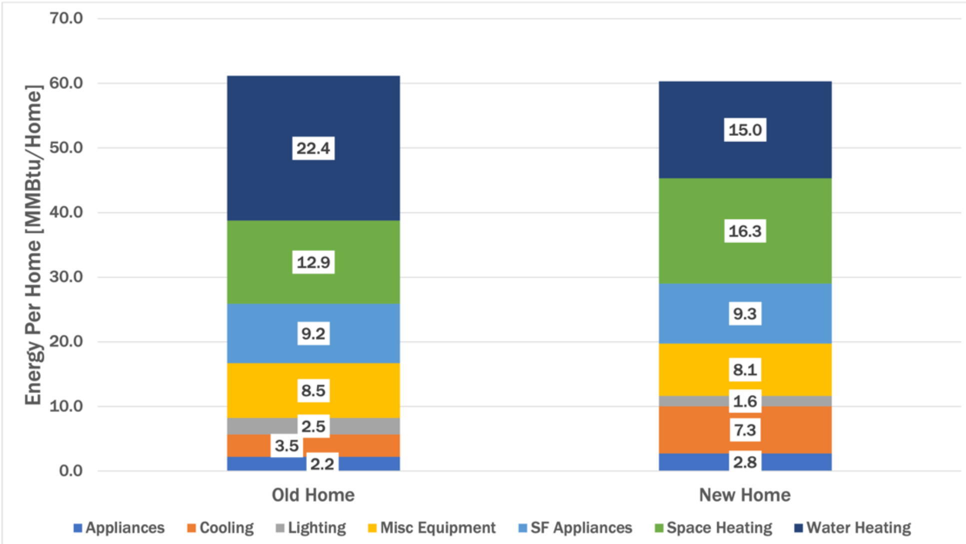

Figure 18: New homes vs old homes, weighted average energy usage.

Figure 18 suggests that the **overall energy usage of new homes is similar to that of old homes.** This is perhaps a surprising result, given the multitude of energy efficiency upgrades required by the Title 24 Building Energy Codes. Figure 18 is likely the result of demographic idiosyncrasies and/or user behavior changes. For example, new homes are on average larger than old homes. In the Western United States, homes built between 2000 - 2009 were 2,398 sf (on average), whereas those built from 1950 - 1990 were closer to 1,500 sf [25]. In addition to housing size, it is possible that energy savings directly incentivize consumers to use more energy than they otherwise would have (rebound effect). Comparing by appliance type, it is notable that new homes use less energy for lighting and water heating, likely due to innovations in light emitting diodes (LEDs) and efficient water heaters, but that new homes use more energy for space heating and cooling, likely due to some of the aforementioned effects. In general, **efficiency gains may compete with demographic idiosyncrasies and user behavior changes, with overall impact being defined by the largest driver.**

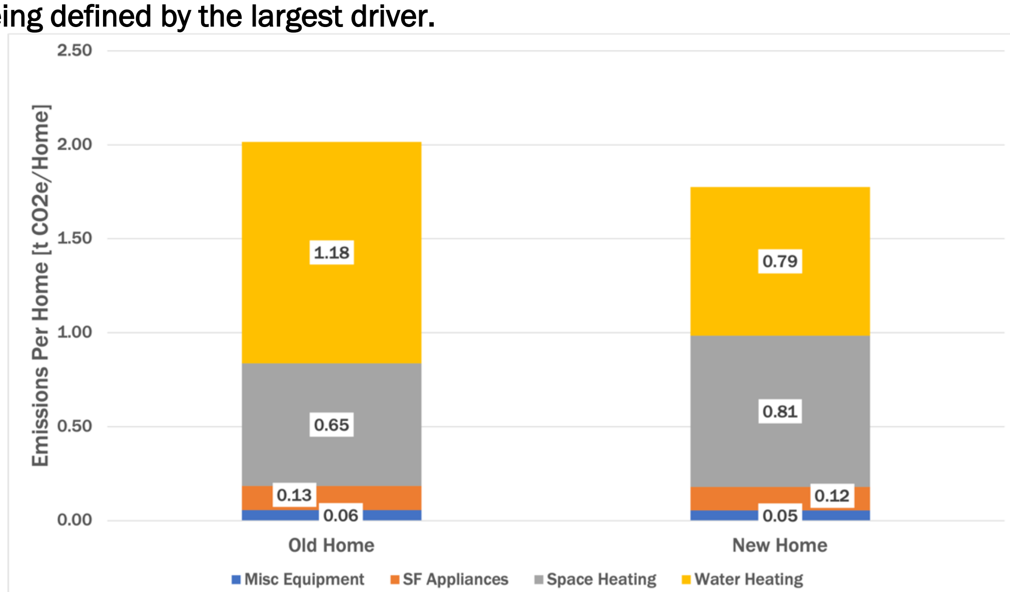

Figure 19: New homes vs old homes, weighted average combustion emissions.

On an onsite emissions basis, there is a larger difference between new homes and old homes. New homes produced less emissions from water heating because they require less energy for said service (Figure 18). Conversely, new homes produce more emissions for space heating because they require more energy for that service (Figure 18). New homes consume more energy for cooling and appliances, but these electric loads produce no onsite emissions and thus do not impact Figure 19.

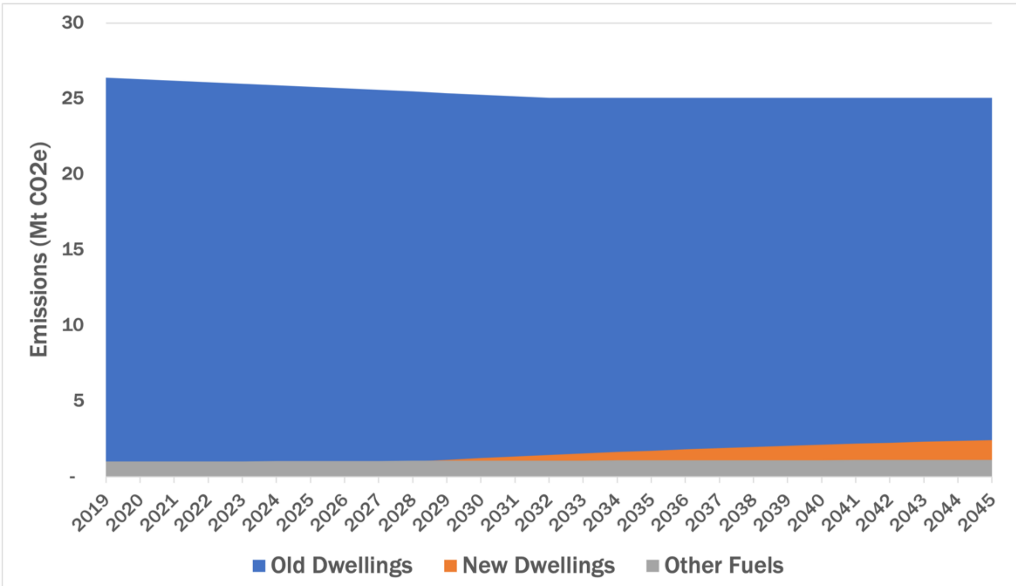

Figure 20: System-wide emissions, new homes vs old homes.

Figure 20 demonstrates that new homes have marginal impact on an energy/emissions basis. This is because the 2045 housing stock will be populated by mainly old homes. While the takeaway here is seemingly obvious, Title 24 standards are currently aimed at new homes and large retrofits only. As was mentioned in interviews with experts and documented in the companion study “Pathways to Carbon Neutrality in California | Clean Energy Solutions that Work for Everyone - Summary of Interview and Workshop Findings” [26], **if California is to realize any real progress in the Residential sector, the state should consider creative policies/strategies that fairly, effectively, and non-invasively improve the existing housing stock.** For instance, one recommendation involved implementing policies at the point of sale, giving homeowners some prescribed period of time from purchase to install required energy efficiency and/or electrification upgrades. Another option is to regulate appliance sales, targeting manufacturers and distributors rather than residents.

Figure 21 illustrates the baseline 2045 load shape. In comparison to Figure 11, Figure 21 includes the growth of new homes, as well as the gradual installation of baseline appliances shown in Table 2. The baseline 2045 grid shape is quite similar to the 2019 grid shape, with the exception that the peak has increased from 21.56 GW to 23.03 GW, implying that the grid will require an additional ~1.47 GW of capacity to satisfy increased electricity demand coming from new homes. As a result of the peak increase, there is also a slight decrease in the grid utilization factor. However, it should be emphasized that Figure 21 does not yet consider the growth of EVs, PVs, batteries, or demand response, which will inevitably change the baseline picture.

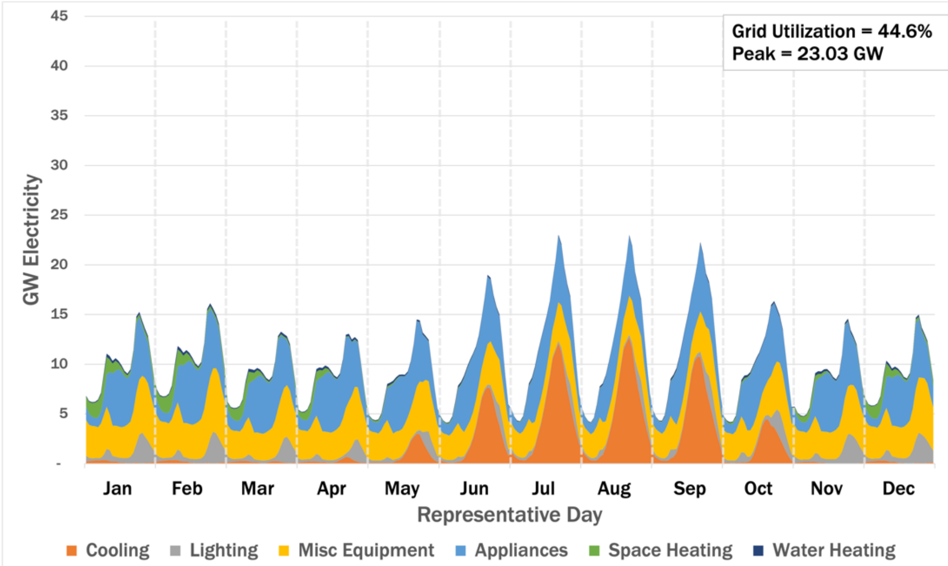

Figure 21: Baseline 2045 residential load shape.

Insights Gained From Building Block Scenarios

In the building block scenarios, ResLEAP tests the efficacy of individual technologies or policies. Results are shown for the following technologies:

- *Space Heating*: space heat pumps and electric resistance furnaces
- *Water Heating*: water heat pumps, electric resistance water heaters, solar water heaters with gas backup, and solar water heaters with electric backup

In all scenarios, fossil fuel appliance sales are reduced over time, being replaced with electric appliance sales. The adoption rate used in all scenarios is shown in Figure 22. Here, when the Technology Fraction equals zero, all retiring fossil fuel appliances are replaced with baseline options (technologies in Table 2); however when the Technology Fraction equals one, all retiring fossil fuel appliances are replaced with electric options (technologies in Table 7).

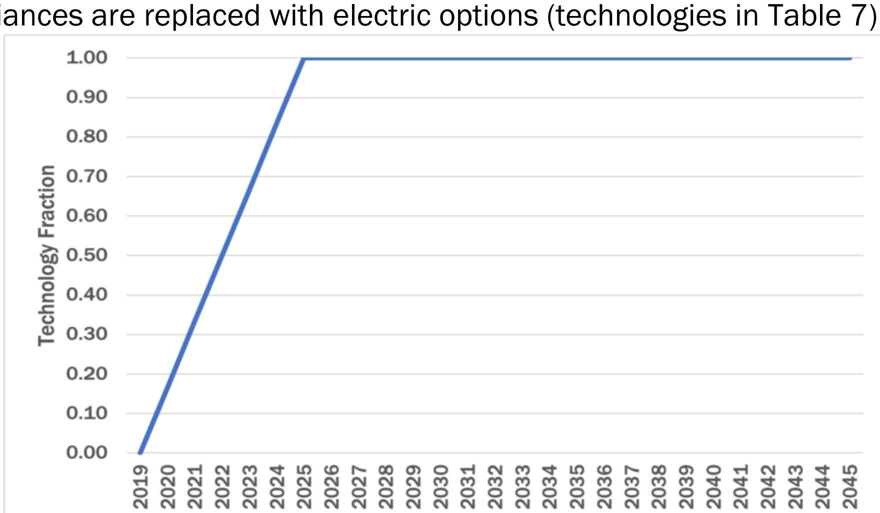

Figure 22: Adoption rate in all scenarios.

Figure 23 shows the cumulative societal cost or benefit realized when residents replace retiring appliances with various space or water heating options. Figure 23 is on a present-value basis and is compared to the baseline. Cost and benefits are broken down by CAPEX and fuel costs. Note that in Figure 23, offsite power plant investments are not included, however fuel spending is included by assuming a constant electricity price of $205.10/MWh and a constant gas price of $46.542/MWh [15].

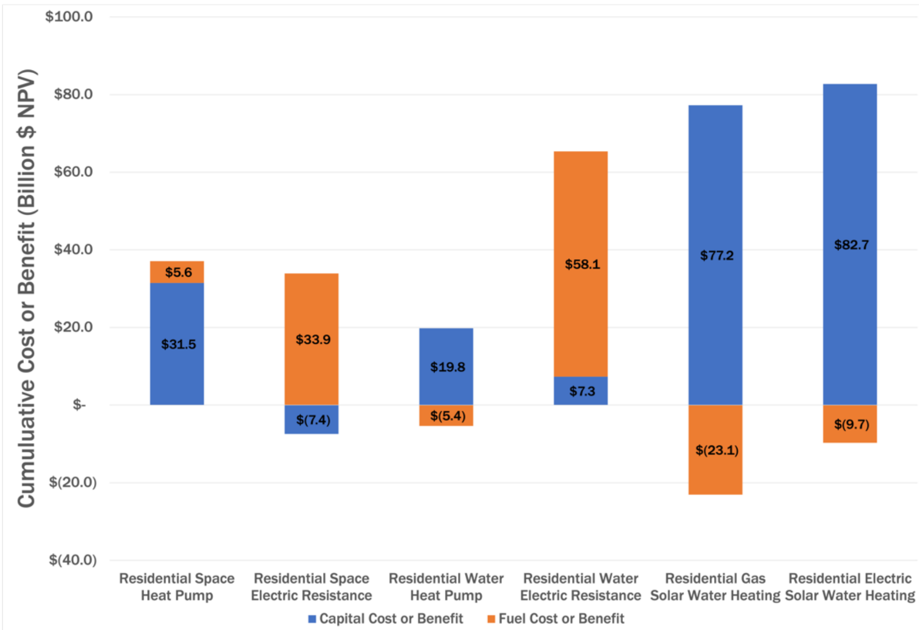

Figure 23: Space & water heating, economics.

Figure 23 can be understood by recalling each technology's technoeconomics:

- **Space Heat Pumps:** have a higher installed cost ($15,478/unit) than baseline NG furnaces ($6,283/unit), and thus significant capital investment is required. Residents see a small increase in fuel costs because space heat pump efficiency gain falls just short of the required 4.4 ratio (Figure 16).
- **Electric Resistance Furnaces:** residents in the state would collectively see about $7.4 billion in upfront savings by purchasing electric resistance furnaces. This is because electric resistance furnaces ($5,135/unit) are cheaper than the NG baseline alternative ($6,283/unit). However, electric resistance furnaces are not efficient enough to make up the cost difference between electricity and NG (Figure 16), and thus residents see a $33.9 billion increase in fuel costs.
- **Water Heat Pumps**: perform well because 1) they are similar enough to the baseline alternative from a capital cost perspective -- $4,061/unit for a water heat pump compared to $2,269/unit for a NG water heater, and 2) they overcome the efficiency requirement needed to generate fuel benefits (Figure 16).
- **Electric Resistance Water Heaters:** perform similarly to electric resistance space heaters, in that residents incur smaller capital costs but larger fuel costs.

[15] Assuming a constant electricity price is least accurate in scenarios where the existing grid peak is greatly exceeded.

- **Solar Water Heaters:** are very expensive, however they overcome the efficiency boundary (Figure 16), resulting in fuel savings. Despite being more efficient, electric solar water heaters generate less fuel savings than gas solar water heaters because electricity is more expensive than NG.

Figure 24 shows the cumulative emissions reductions by 2045 for each technology. This metric captures the cumulative impact of 1) reducing onsite combustion emissions, 2) reducing onsite NG fugitive emissions, and 3) increasing F-Gas fugitive emissions, with most of the differences coming from contributions one and three. Offsite power plant emissions are excluded from Figure 24.

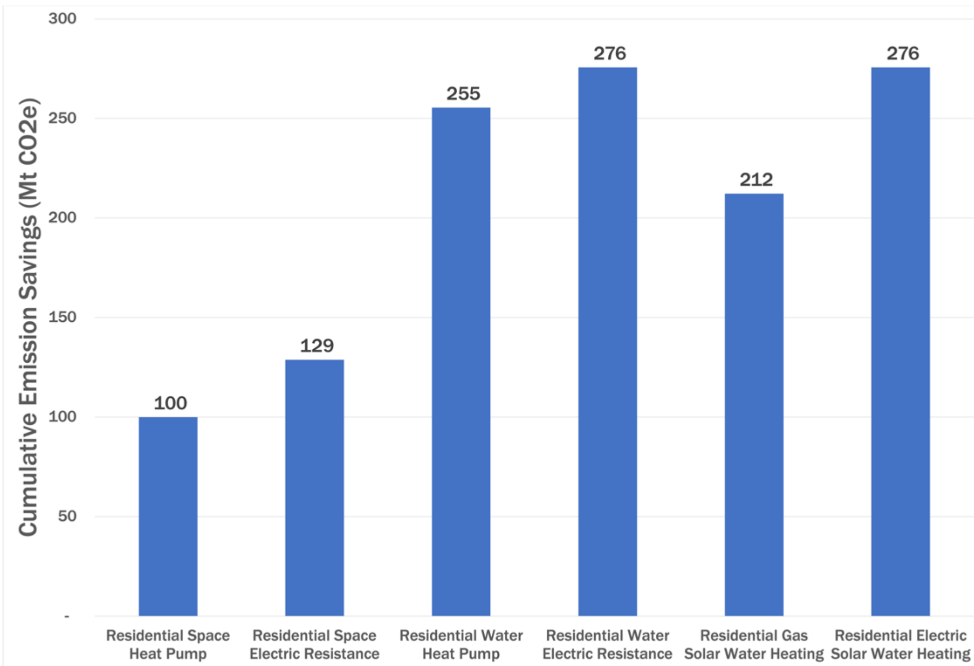

Figure 24: Space & water heating, abatement potential.

In Figure 24, note that all water heating options abate more emissions than space heating options; this is because homes in California use more energy for water heating than space heating (Figure 9). Comparing the space heating options, electric resistance furnaces abate more emissions than the space heat pumps; this is because space heat pumps add F-Gases into the system. Amongst the water heating options, electric resistance water heaters and electric solar water heaters mitigate the most emissions. Water heat pumps mitigate less due to F-Gases, and gas solar water heaters mitigate even less due to continued (but reduced) burning of NG.

Figure 25 is generated by dividing Figure 23 by Figure 24 – the result is the cost of carbon abatement, which (imperfectly) attempts to capture many of the pros and cons discussed above in a single metric. A low cost of carbon abatement means a program requires less money to abate more CO_2e. The major takeaway from Figure 25 is that **water heat pumps have potential to be an important technology for the state, mitigating large amounts of CO_2e while being cost effective.** For space heating, electric resistance furnaces perform best on a cost of carbon abatement basis.

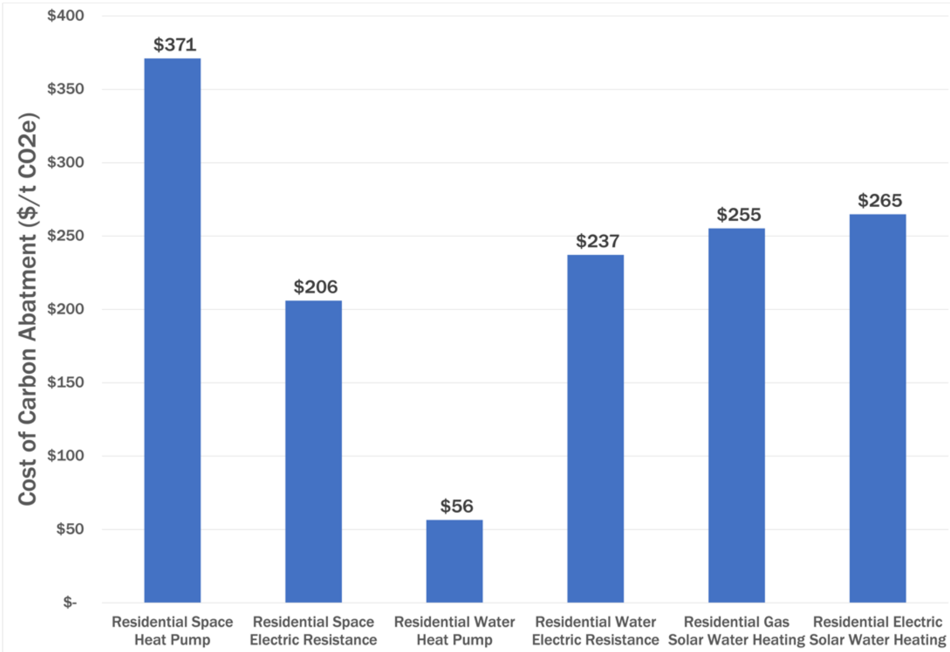

Figure 25: Space heating & water heating, cost of carbon abatement.

Figures 26 and 27 demonstrate the importance of AC scrapping to the efficacy of space heat pumps. Figure 26 shows annual CAPEX cost or benefits relative to the baseline scenario. As heat pumps are more expensive than NG furnaces, society spends more upfront capital on heaters; however this is partially offset by society spending less on ACs over time, with fewer homes requiring AC replacements. Figure 27 shows F-Gas emissions over time relative to the baseline scenario. F-Gas leaks from space heat pumps increase over time, however F-Gas leaks from ACs decrease over time, with an overall net increase. F-Gases increase more dramatically starting in about 2035, when heat pumps are installed in homes without ACs. Overall**, space heat pumps would be less economically and environmentally effective without AC scrapping. Policymakers should consider prioritizing space heat pumps in homes that already have ACs.**

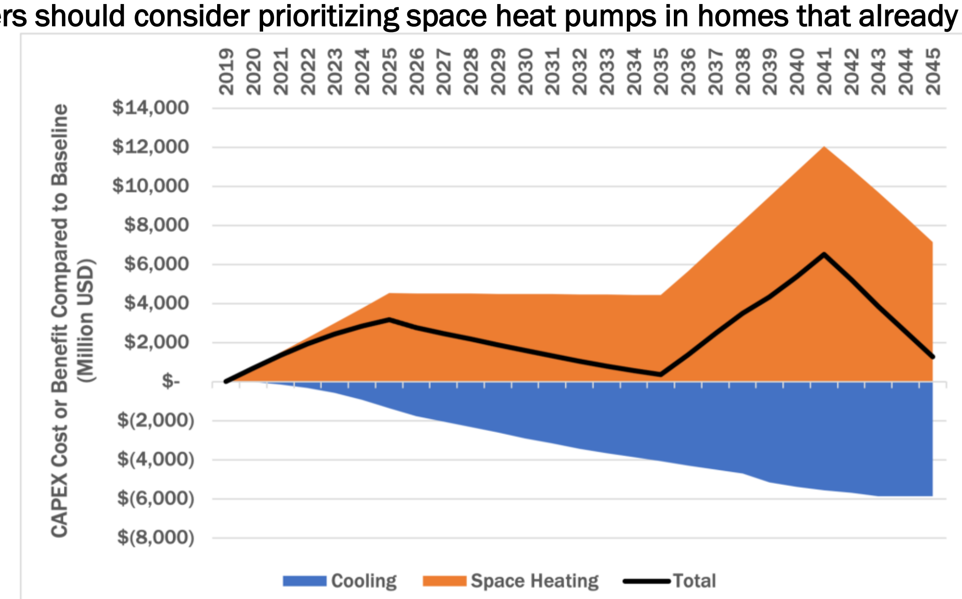

Figure 26: Space heat pump scenario, CAPEX compared to baseline.

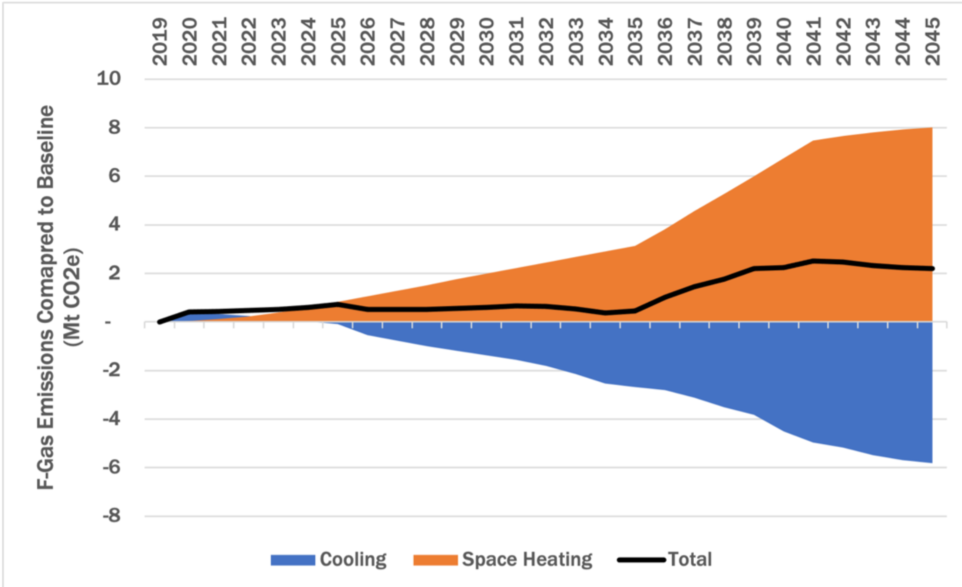

Figure 27: Space heat pump scenario, F Gas emissions compared to baseline.

Figures 28 and 29 demonstrate the relationship between cost of carbon abatement and geographic location. For both water and space heat pumps, cost of carbon abatement is indeed a function of climate zone. In Appendix F, linear regressions are performed in order to quantitatively explain behaviors shown in Figures 28 and 29. At a high level:

- **Water Heat Pumps:** cost of carbon abatement is smaller for climate zones that use more NG for water heating. This is because in these climate zones, 1) water heat pumps mitigate more NG combustion emissions while adding the same amount of F-Gas emissions (F-Gas emissions are assumed to be independent of usage [6]), and 2) residents see greater fuel savings in switching from a NG water heater to a water heat pump.
- **Space Heat Pumps:** cost of carbon abatement is smaller for climate zones that 1) use more NG for space heating, and 2) have a higher saturation of ACs compared to NG furnaces. The latter effect occurs because the economic and environmental benefits of AC scrapping is felt for longer (there are more ACs to scrap).

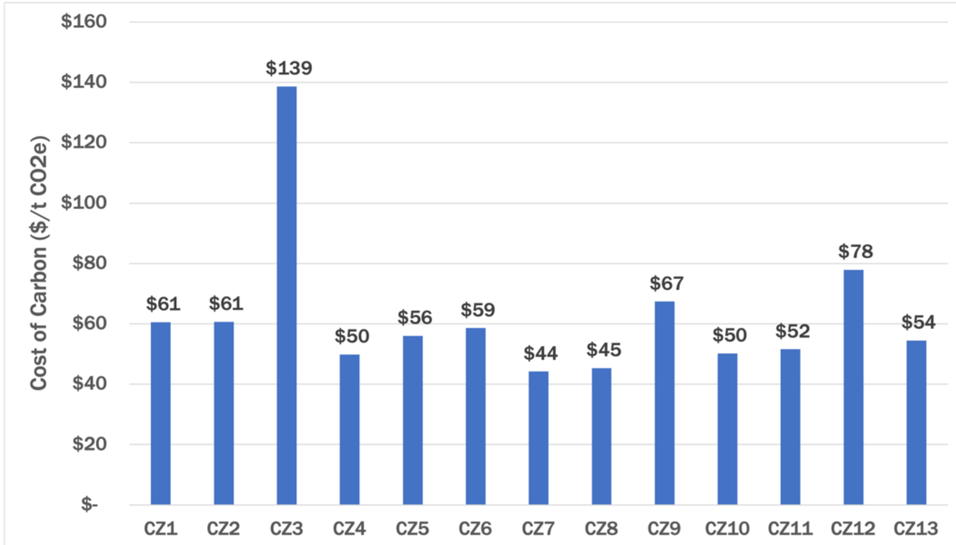

Figure 28: Water heat pump, cost of carbon abatement by climate zone.

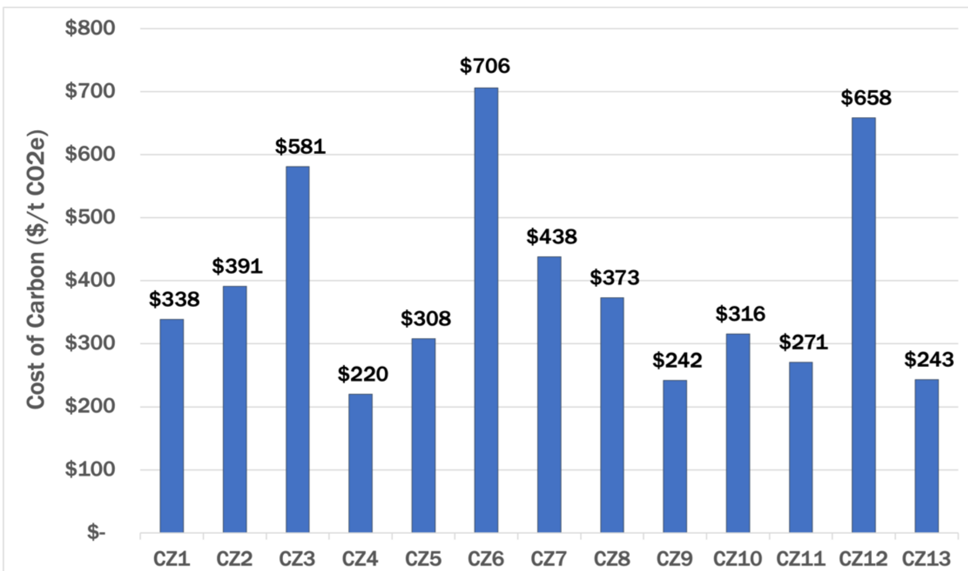

Figure 29: Space heat pump, cost of carbon abatement by climate zone [16].

Figures 28 and 29 ultimately emphasize the importance of geographic context, which could encourage policymakers to implement programs in stages while working closely with local governments. In particular, California **could consider implementing incentives first in those geographic regions that see more favorable returns; then as manufacturing and supply chains scale, costs may drop to a point where equally favorable returns can be seen in other geographic regions.** A program like this would possibly require careful consideration of equity and fairness.

---

[16] Note that climate zone three is shown in both Figure 28 and 29 to have a high cost of carbon abatement, especially in the case of water heat pumps. These results are somewhat a consequence of data processing methods used. Climate zone three contains only about 1.8% of homes in the state, and thus irregularities in climate zone three have little impact on state-wide values.

In Figure 31, the cost of carbon abatement for space and water heat pumps is recalculated, assuming aggressive F-Gas policies are implemented. In particular:

- EOL F-Gas leak rates are reduced over time, from current levels in 2020 to 0% in 2045. In the real world, this would imply implementing responsible EOL management programs. The cost of these programs is currently unknown and thus is set to $0 within ResLEAP.
- In addition, sales of appliances that utilize R-410A and HFC-134A (refrigerators, freezers, space and water heat pumps, ACs) are gradually replaced over time with equivalent processes that utilize low-GWP refrigerants (CO_2 assumed in this study). In particular, low-GWP refrigerant sales are ramped up from zero in 2025 to one by 2035, which implies the state beginning to sell low-GWP appliances in 2025 and selling only low-GWP appliances by 2035. Low-GWP appliances are assumed to have the same installed cost as high-GWP appliances used today.

These two effects are modeled using unitless parameters, shown below in Figure 30:

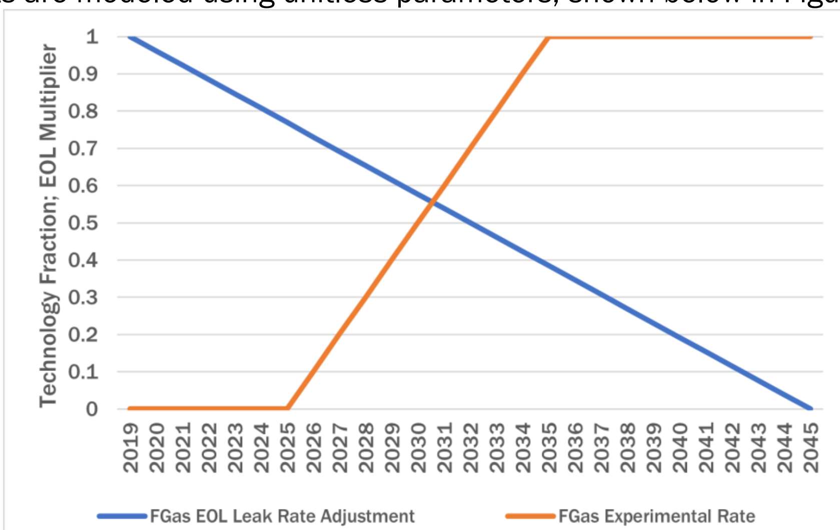

Figure 30: F Gas levers

In Figures 31 and 32, space and water heat pump cost-benefit analyses are redone assuming 1) reduced EOL emissions, 2) increased sales of low-GWP appliances, and 3) both 1 and 2 combined. Interestingly, space heat pumps are more sensitive to the F-Gas measures; this is because space heat pumps produce more F-Gases per unit (Table 8). Notice as well that the best-case space heat pump ($232/t) is approaching the cost of carbon abatement for electric resistance furnaces ($206/t).

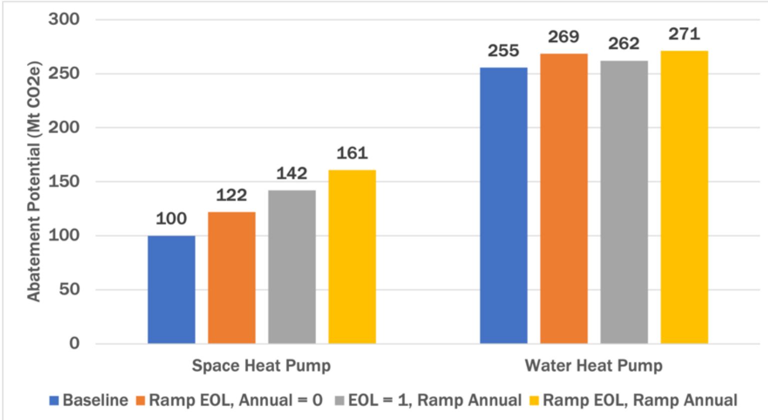

Figure 31 Heat pump abatement potential and F-Gas sensitivity.

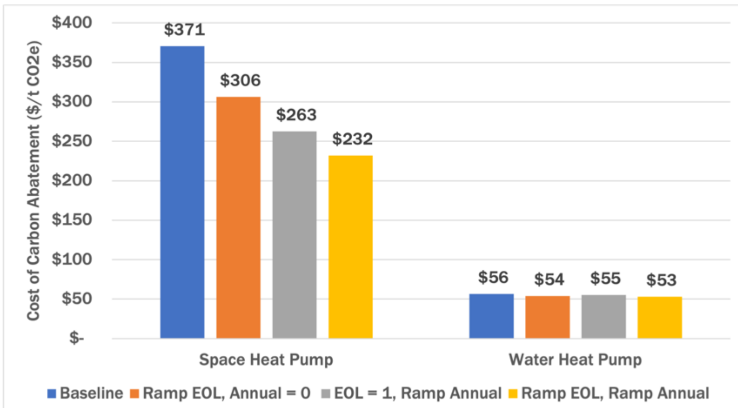

Figure 32: Heat pump cost of carbon abatement and F-Gas sensitivity.

An additional sensitivity analysis is provided in Appendix G.

Insights Gained From Combined Scenarios

Building block scenarios can be stacked to create combined scenarios that decarbonize the entire Residential sector. In all three combined scenarios considered, NG appliances – including space heaters, water heaters, range ovens, and clothes dryers – are electrified. Efficient electric appliances (ACs, refrigerators, clothes washers, dishwashers) are also used instead of the less efficient counterparts. In the Decarbonize Residential scenario, during the brief electrification ramping period from 2020 to 2025, efficient NG technologies are sold instead of less efficient NG alternatives. The major difference between the scenarios is the breakdown between heat pump and electric resistance heating:

- **Decarbonize Residential:** 75% heat pump / 25% electric resistance.
- **Heat Pump Electrification:** 100% heat pump / 0% electric resistance.
- **Resistance Electrification:** 0% heat pump / 100% electric resistance.

Figures 33 demonstrates the impact of technology choice on the residential grid shape.

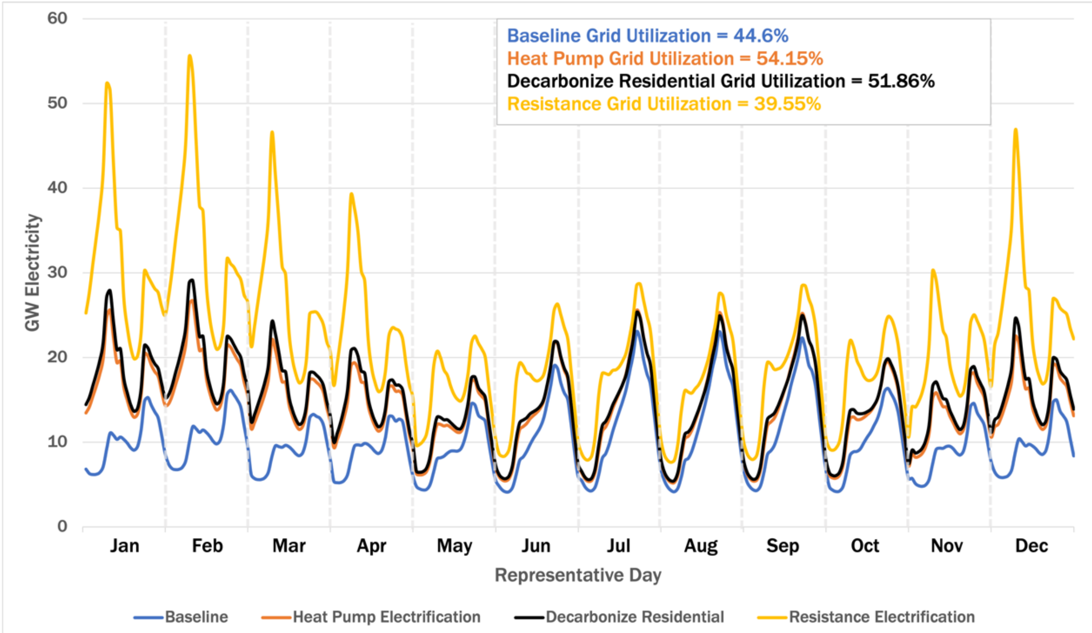

Figure 33: Combined scenarios, 2045 residential load shapes.

In the Resistance Electrification scenario, NG furnaces and NG water heaters are replaced with electric resistance furnaces and electric resistance water heaters. The now winter-peaking grid shape is rather problematic, adding 32.46 GW of capacity while dropping grid utilization from 44.6% to 39.55% (compared to the baseline) [17]. In the Heat Pump Electrification scenario, NG furnaces and NG water heaters are replaced with space and water heat pumps. Due to heat pump's improved efficiency, the grid peak increases by only 3.67 GW, and grid utilization improves by 9.55% (compared to the baseline). In the Decarbonize Residential scenario, a 75/25 split of heat pump vs electric resistance heating is used, with performance being somewhere in between the two extremes: a 6.08 GW increase in capacity, and a 7.26% improvement in grid utilization (compared to the baseline). The main takeaway for policymakers is that electrification of the Residential sector -- if done primarily with heat pumps -- will create a dual-peaking grid that 1) has a higher utilization factor, and 2) requires only modest infrastructure investment. Appendix H contains additional analysis on the Decarbonize Residential grid shape.

Figures 34 - 36 demonstrate the effect of implementing F-gas programs. Note that Figures 34 - 36 do not include emissions from offsite power plants.

[17] Figures 23 and 25 assume constant electricity prices. For electric resistance heating in particular, this assumption may be quite generous, given the infrastructure investment likely required to satisfy the new peak. The year-two study will correct this assumption by explicitly including power plant investments.

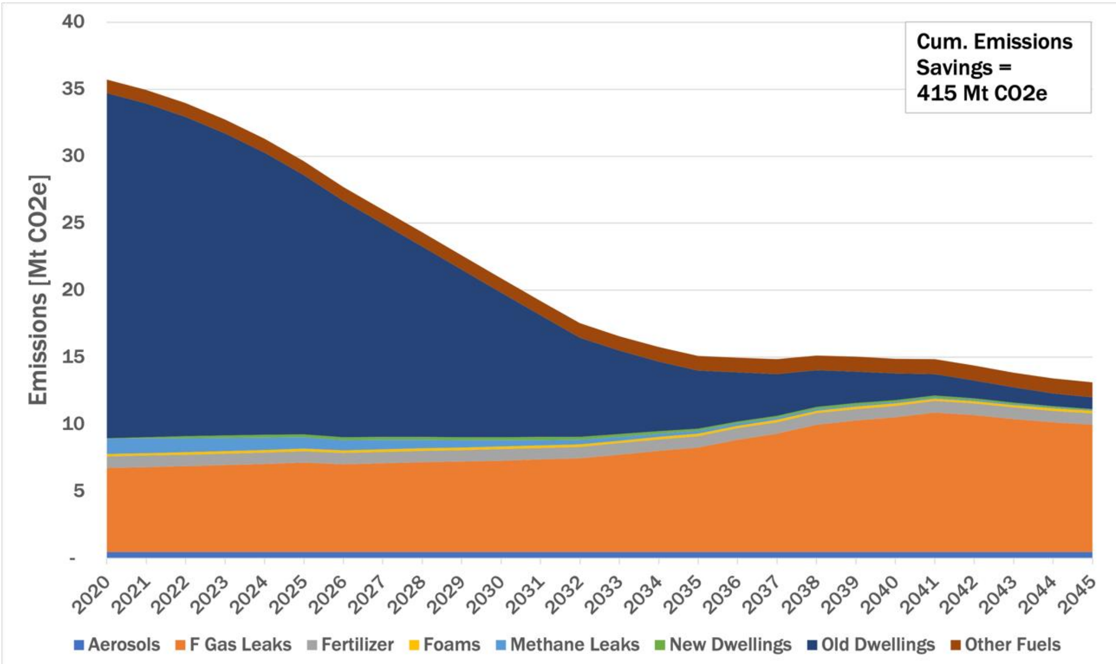

Figure 34: Decarbonize residential, no F Gas programs.

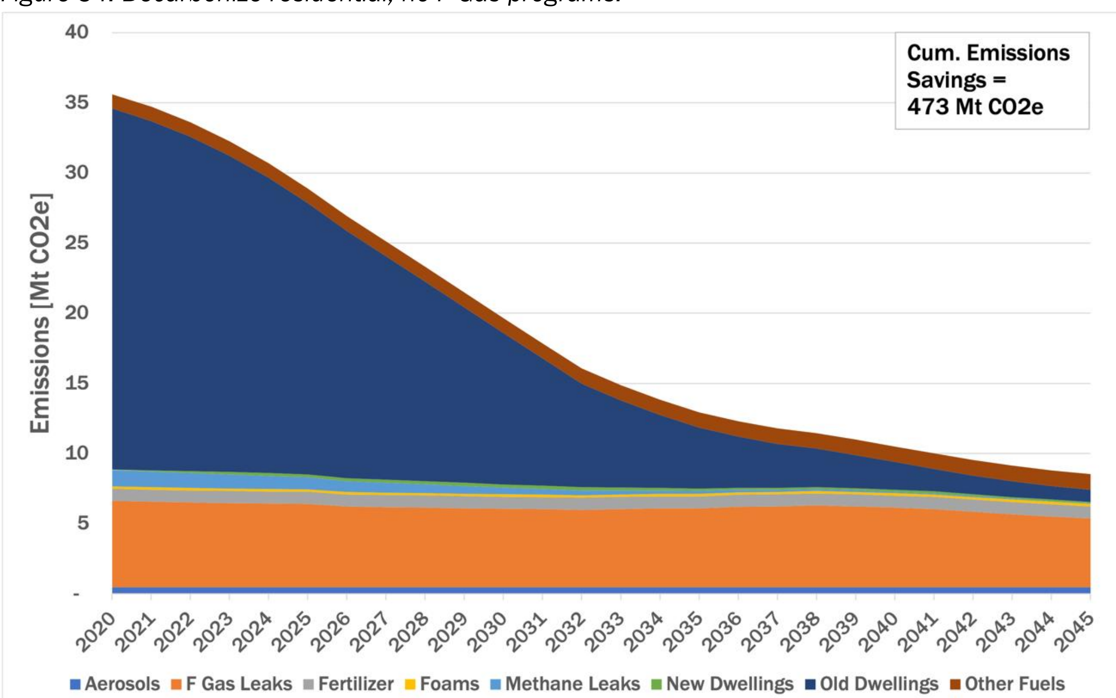

Figure 35: Decarbonize residential; EOL F Gas programs.

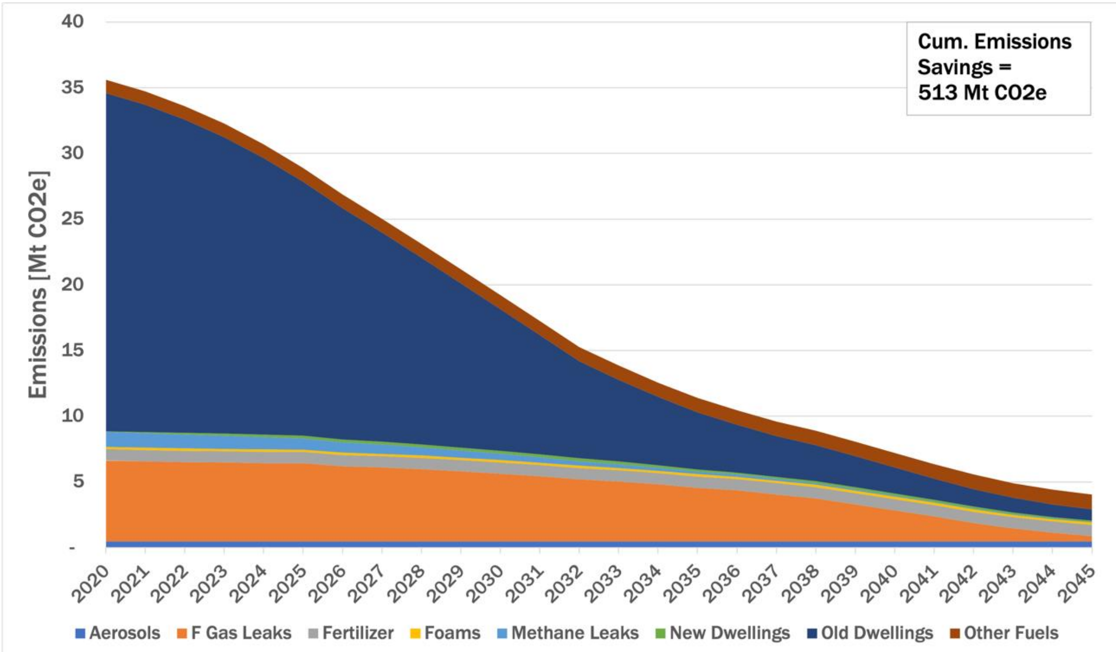

Figure 36: Decarbonize residential, EOL F Gas programs and Low-GWP refrigerants.

Figure 34 can be considered a worst-case scenario as it pertains to F-Gases. In this scenario, no adjustments are made to CARB's EOL leak rates; this assumes that 1) CARB's EOL emission factors are 100% accurate, and 2) the state implements no EOL management programs. The results are somewhat discouraging; while almost all combustion emissions are mitigated, there are still significant F-Gas fugitive emissions, with the state ultimately failing to reach near net-zero by 2045.

Figure 35 demonstrates the effect of implementing responsible EOL management practices, ramping EOL leak rates down to 0% by 2045. Despite introducing millions of space and water heat pumps into the system, just by implementing responsible EOL management practices, F-Gas emissions stay relatively constant throughout the period. However, the state is still not able to reach near net-zero, mainly due to *annual* F-Gas emissions. In Figure 36, EOL leak rates are ramped down, and in addition, sales of low-GWP heat pumps are ramped up. Only then is the state able to reach *near* net-zero, still emitting about 4.04 Mt of CO_2e by 2045.

Figure 37 below demonstrates that, of these 4.04 Mt, 3.57 Mt stem from emission sources that cannot be altered using techniques in ResLEAP (aerosols, fertilizer, foams, and combustion of minority fuels). It will be difficult for the state to systematically mitigate these final emission sources because 1) the sources are heterogeneous in nature, and 2) there is little data available to support modeling.

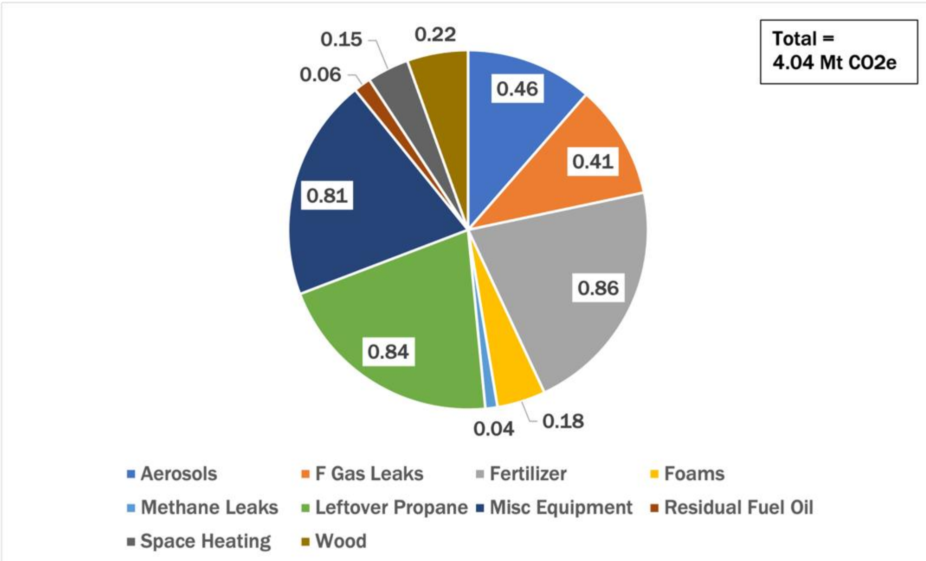

Figure 37: Decarbonize residential 2045 emissions.

Figure 38 shows a Marginal Abatement Cost Curve (MACC) for the most aggressive Decarbonize Residential scenario (the scenario shown in Figure 36). On the MACC plot [18], the x-axis is the amount of carbon each program is responsible for mitigating, and the y-axis is the cost of carbon abatement for each individual program.

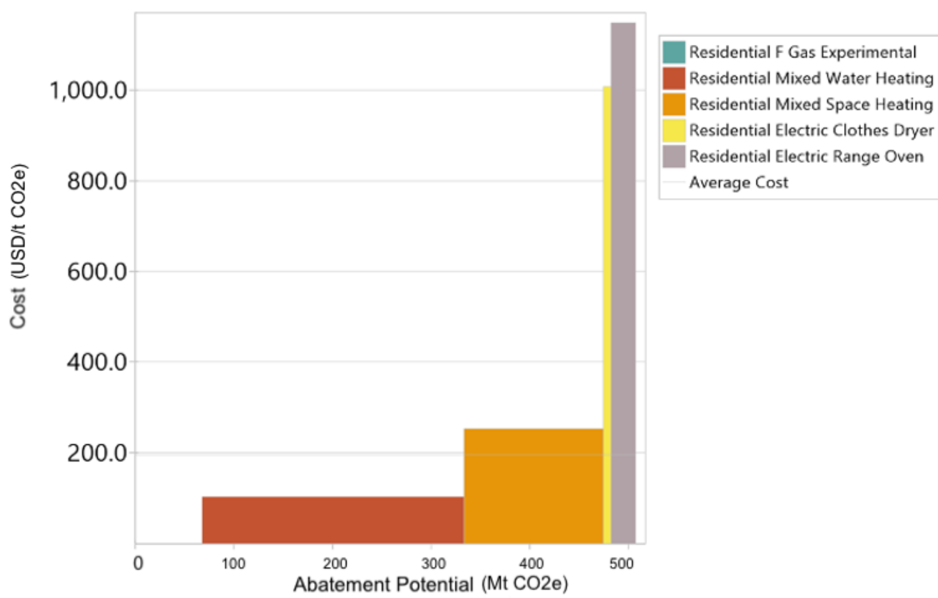

Figure 38: Decarbonize residential MACC Plot (Adapted From LEAP Model [27]).

[18] The MACC plot is not entirely inclusive, ignoring small contributions from efficient gas heaters installed during the brief electrification ramping period from 2020 to 2025. Mixed Water Heating and Mixed Space Heating blocks assume low-GWP sales are ramped from 0% in 2025 to 100% in 2035, with no adjustments made to capital costs. The F-Gas building block represents a program that gradually installs responsible EOL management practices, linearly decreasing leak rates to 0% by 2045; the cost of such a program is unknown at this time, and thus is currently set to $0.

The MACC plot demonstrates that the mixed water heating building block mitigates the most emissions at a cost of $102.3/t. The next biggest contributor is the mixed space heating building block, at a cost of $252.3/t. The EOL F-Gas building block also mitigates significant carbon. Smaller building blocks such as electric range/ovens and electric clothes dryers reduce less carbon at higher cost, demonstrating that it will become increasingly expensive to decarbonize the sector as the state gets closer to net-zero. Figure 38 can be seen as a priority list, with low-GWP water heat pumps being priority one, followed by low-GWP space heat pumps and EOL F-Gas emissions.

Figure 39 summarizes the final exogenous decisions used for the most aggressive Decarbonize Residential scenario (the scenario shown in Figure 36). Levers were chosen such that the Decarbonize Residential scenario would be forced as close to net-zero as reasonably possible, within constraints of the model. In a sense, Figure 39 demonstrates approximately "what it will take" to decarbonize onsite residential emissions by the year 2045. In particular, in order to decarbonize the sector without the use of negative emissions or scrapping , the state must in some form:

1. Linearly ramp up the adoption rate of electric appliances to 100% by 2025.
2. Install responsible EOL F-Gas management programs so as to linearly decrease EOL F-Gas leak rates to 0% by 2045.
3. Begin installing innovative technologies that employ low-GWP refrigerants (CO_2 assumed here) by the year 2025, and in addition, ramp up the sales fraction of these technologies to 100% by the year 2035.

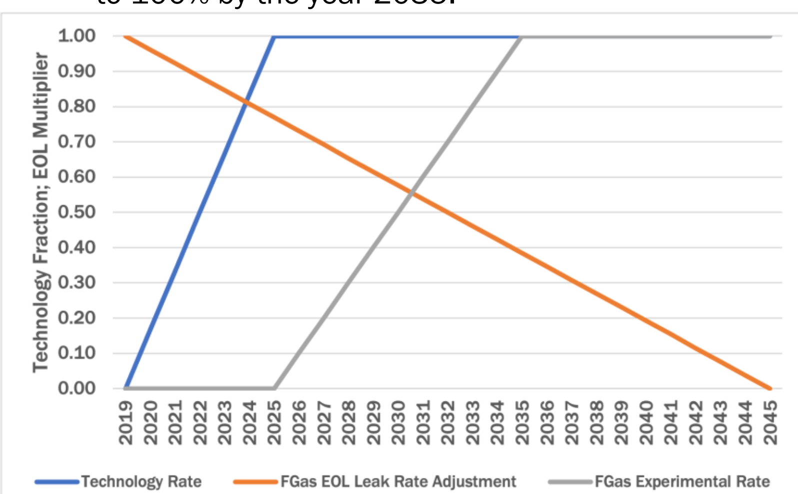

Figure 39: Decarbonize residential exogenous levers.

It is important to note that Figure 39 is not binding – the model can be forced to near net-zero with other configurations. That being said, **the overall speed with which policymakers must act to reach California state goals must be emphasized.**

Conclusions

This study compares electric space and water heating technology options. Water heat pumps stand out as a technology that has a relatively low cost of carbon abatement, meaning it mitigates more carbon for less cost. Water heat pumps perform well because they are closer in cost to the NG baseline alternative, because they offer substantial efficiency improvements over stock NG water heaters, and because they have a small F-gas charge size. In addition, as water heating is less peak driven, water heat pumps do not add substantially to grid capacity requirements.

Electric resistance furnaces outperform space heat pumps on a cost of carbon abatement basis. However, space heating is a peak driven service, and thus the grid can only accommodate modest penetration of electric resistance furnaces before requiring substantial grid build-outs. Space heat pump performance can be improved by: 1) focusing on regions that use more NG for space heating, 2) installing space heat pumps in homes that already have central ACs, 3) pairing space heat pump programs with careful EOL management practices, and 4) using low-GWP space heat pumps.

This study also tested the effect of technology choice on grid shape. 100% reliance on heat pumps results in the preferred grid, requiring only 3.67 GW of added capacity and resulting in a 9.55% improvement in utilization. 75% reliance on heat pumps requires 6.08 GW of added capacity and improves utilization by 7.26%. By comparison, 100% reliance on electric resistance heating requires 32.46 GW of added capacity, with grid utilization dropping by about 5%.

This study is unique in its granular accounting of F-Gases. California will not reach net-zero without careful consideration of F-Gases, especially if the state is to rely on heat pumps to serve space and water heating needs. Just by linearly reducing EOL leak rates to zero by 2045, the state can keep F Gas emissions steady while installing millions of heat pumps. To reach true net-zero without carbon offsets, the state will need low-GWP heat pumps, currently available (but expensive) overseas.

This study assumes zero scrapping. Scrapping involves intentionally removing an appliance before its natural EOL. Scrapping mitigates the full benefit of a consumer's initial investment. In addition, scrapping can potentially be seen as invasive. To avoid scrapping, this study electrified 100% of heater sales by 2025. This is a dramatic pace that should be a signal to policymakers to act [19].

A follow on study is planned to include the following:

- ResLEAP will include category 4 technologies (PVs, batteries, and demand response) and possibly category 1 technologies (home efficiency improvements).
- Offsite power plants will be included in the study's scope. Doing so may have a substantial impact on emissions and economics, ultimately leading to a more complete

[19] Note that in this study, a uniform adoption rate across all technologies was used; said adoption rate could likely be delayed slightly for water heaters while still reaching net-zero.

cost-benefit-analysis. Final conclusions may be subject to change upon inclusion of offsite generators.
- EV charging will be added, which is somewhat attributable to residential load.
- More technology combinations will be tested. In this study, the combined scenarios only tested 100% electric resistance heating, 100% heat pump heating, and 75% heat pump / 25% electric resistance heating. The second-year study could examine, for example, the effects of pairing space heat pumps with electric resistance water heaters. Solar water heater options also require further study.
- Capital cost may be made a function of the adoption rate using supply curves and learning rates.
- F-Gas leak rates (both annual and EOL) require further investigation

Please note that many of the figures and tables shown in this report were generated using LEAP's data processing and visualization software [27].

Appendices

Appendix A: Why LEAP?

The stock and flow model is built in the Low Emissions Analysis Platform (LEAP), developed by the Stockholm Environment Institute. LEAP is a tool used for analyzing energy/climate policies and strategies. According to LEAP's creators, the software has "been adopted by thousands of organizations in more than 190 countries worldwide," with its users including "government agencies, academics, non-governmental organizations, consulting companies, and energy utilities" [28]. The use of LEAP was intentional, with motivations listed below:

- Several modeling approaches are available in LEAP. They are quite instructive, being logical, easy-to-understand, and well agreed-upon amongst the scientific community.
- LEAP's tree structure allows for highly granular, customizable accounting.
- In LEAP, smaller "building-block" scenarios can be used to test the impact of individual technologies or policies. Afterwards, building-blocks can be stacked to test the combined impact of many technologies and policies. Via this structure, it is possible to test the efficacy of individual measures in a vacuum, while also testing the efficacy of measures in the context of the greater economy.
- The building-block structure also makes it relatively easy to experiment with a wide variety of technology choices.
- LEAP comes with a helpful set of emission factors and fuel data.
- LEAP makes it relatively easy to generate informative, creative results.
- LEAP's graphical user interface has inherent advantages over black-box models, with all data entries and key assumptions being exposed to the user.

Appendix B: Key Insights From Literature

Technical Conclusions

- Electrification is an important strategy for decarbonizing residential buildings. Economic savings can be achieved in many cases [7, 16]. Furthermore, electrification can presently reduce emissions by 30% - 60%; these savings are estimated to increase to 80% - 90% by 2050 [7].
- Electrification is most economical in the following contexts: new construction (due to mitigating retrofit costs), low-rise multi-family buildings (due to economies of scale), homes that do not require electric panel upgrades, and homes that already have ACs (ACs can offset space heat pump costs) [7, 16]. In addition, retrofits perform better when paired with: improvements to space and water envelopes, PVs, and time-of-use electricity rates [16].
- Residential building electrification will lead to a large increase in winter electricity demand. Depending on the breakdown of electric resistance versus heat pump heating, the residential grid shape could even become winter peaking [29]. That being said, increased winter load may improve grid utilization [7], and thus residential electrification may only require modest capacity build outs [16].
- Building electrification is expected to net bring *more* jobs into the economy. Electricians, plumbers, ducting technicians, and transmission sector construction workers will be in high demand. These are high quality jobs [30].

Policy Ideas

- Educate policymakers, consumers, contractors, and distributors [7, 16].
- Increase carbon prices via the cap-and-trade program. This would ultimately increase the cost of NG, further allowing electric appliances to compete [7].
- R&D investment in low-GWP heat pumps and in cheap, “retrofit-ready” plug-and-play solutions [7].
- Redesign electricity rates such that they encourage electrification. Volumetric electricity rates not only discourage electrification, but they are misaligned with actual cost drivers to utilities. Possible re-designs may include utilizing fixed costs and time-of-use rates [7, 16].
- Philosophically rethink building codes. The goal should be to reduce emissions, not necessarily to reduce energy consumption. Fugitive emissions from NG and F-Gases should also be considered when developing policies [7].
- Scale manufacturing capacity of electric appliances. Possible ideas to add confidence amongst suppliers / investors include setting concrete targets and updating the building code to require electric devices [7, 16].
- Incentivize electrification in the most favorable contexts. As mentioned above, this includes all-electric new construction, low-rise multi-family buildings, homes that do not require electric panel upgrades, and homes that already have ACs. Homes that aren’t 100% electric should at least be built to be “electrification ready,” with the proper electric panel size [7].
- Incentivize thermal envelope retrofits amongst old, inefficient homes [7].
- Motivate landlords by offering incentives and low-cost financing [7].

- Consider a branched pruning system when decommissioning NG [30] [20].

[20] In a branched pruning system, homes are electrified by region such that entire gas branches can be shut down or “pruned.” This is done to avoid gas prices rising amongst homes that are slow to electrify. In the counterfactual case, a very small number of gas homes will require the same degree of gas distribution. This would result in the same revenue requirement for gas utilities, however utilities would have to spread their costs amongst a smaller number of ratepayers, therefore increasing the price of NG. This counterfactual case raises equity concerns [30].

Appendix C: E3's Residential Model vs ResLEAP

The *Residential Building Electrification in California: Consumer Economics, Greenhouse Gases and Grid Impacts [7],* published by E3 in 2019, examines the economic effectiveness of various residential building electrification technologies. E3's core modeling approach was highly influential on ResLEAP, with both studies using stock and flow modeling. In general, E3's study should be considered more granular by housing type (multi-family vs single-family) and by housing age (pre-1978, 1990, and new construction), while this study sacrifices this granularity for greater coverage in technology options and geographic scope. Similarities and differences between E3's model and ResLEAP are listed below:

- E3 obtains energy consumption data from the NREL's (National Renewable Energy Laboratory) BEopt software. ResLEAP utilizes the BEopt software for load shapes only [31], instead using the CEC's RASS in tandem with known top-down electricity and gas totals to define energy consumption. This is a significant difference, with E3 relying on modeling data and ResLEAP relying on survey data -- of course, both of these approaches have their own merits and drawbacks.
- For economic data, E3 contracted AECOM to perform cost estimations. Those estimates are a function of housing type and age, as well as geographic location. In this study, E3 / AECOM's dataset is combined with data from the EIA's study titled, "Building Sector Appliance and Equipment Costs and Effectiveness" [13], ultimately to create a new economics dataset that covers a larger range of geographies and technologies.
- The E3 study is restricted in geographic scope to regions around: San Francisco, San Jose, Sacramento, Coastal Los Angeles, Downtown Los Angeles, and Riverside, collectively covering about 50% of the state's households. This study includes all geographic regions in California. Admittedly, significant assumptions were made in data poor areas, resulting in greater uncertainty in these regions.
- E3 breaks homes down by: geography, by low rise multi-family homes versus single-family homes, and by vintage (pre-1978, 1990s, and new construction homes). In this study, homes are broken down by geography and by old homes versus new homes, with all other categorization handled via a weighted average.
- E3's study compares the following technologies: 1) space heat pumps vs a combination of NG furnaces and central ACs, 2) water heat pumps vs NG water heaters, 3) electric resistance vs gas stoves, 4) electric resistance clothes dryers vs NG clothes dryers, and 5) heat pump clothes dryers vs NG clothes dryers. This study includes all of these technologies (except for heat pump clothes dryers), and also models electric resistance furnaces, electric resistance water heaters, solar water heaters, lighting, refrigeration, dishwashers, and more.
- The E3 study factors in emissions from power plants, which is outside the scope of this current study. Emissions from off-site power plants will be included in a follow-on year-two study.
- Both E3 and this study estimate the contribution of NG and F-Gas leaks.

Appendix D: Technology Saturations

It may be useful for policymakers to know where certain types of appliances are located in the state. In general, NG is the dominant fuel in all climate zones -- it is more interesting to see where the minority technologies/fuels are located.

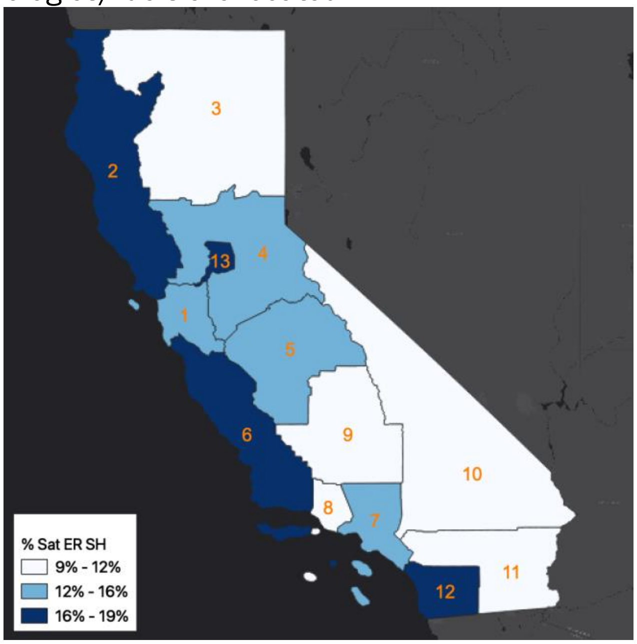

Figure 40: Electric resistance space heating by climate zone.

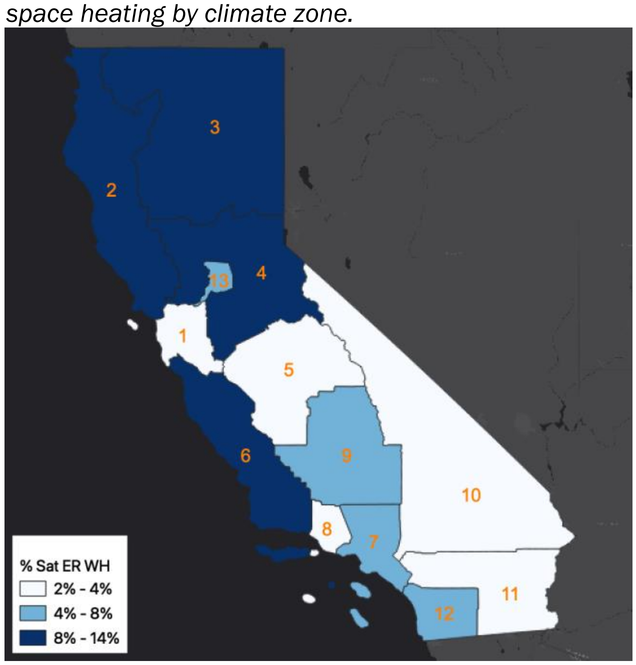

Figure 41: Electric resistance water heating by climate zone.

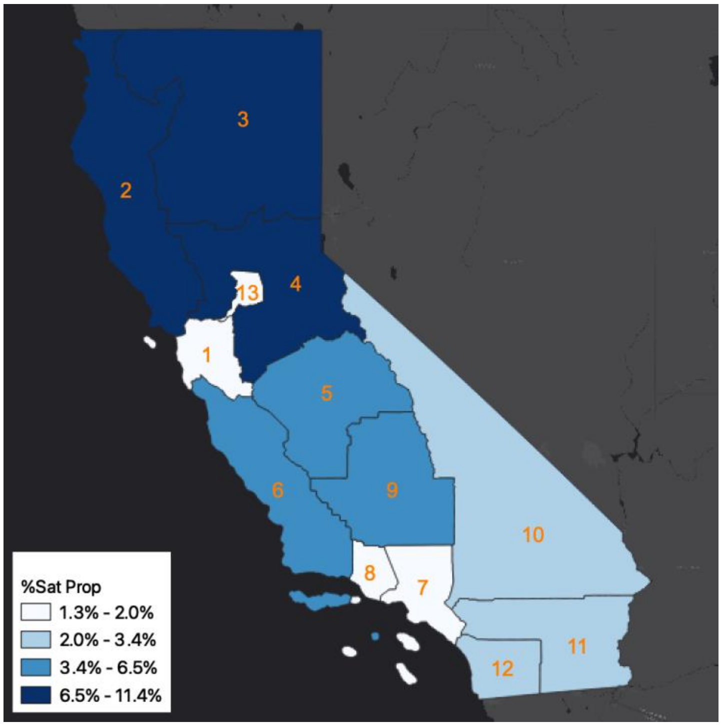

Figure 42: Propane saturation by climate zone.

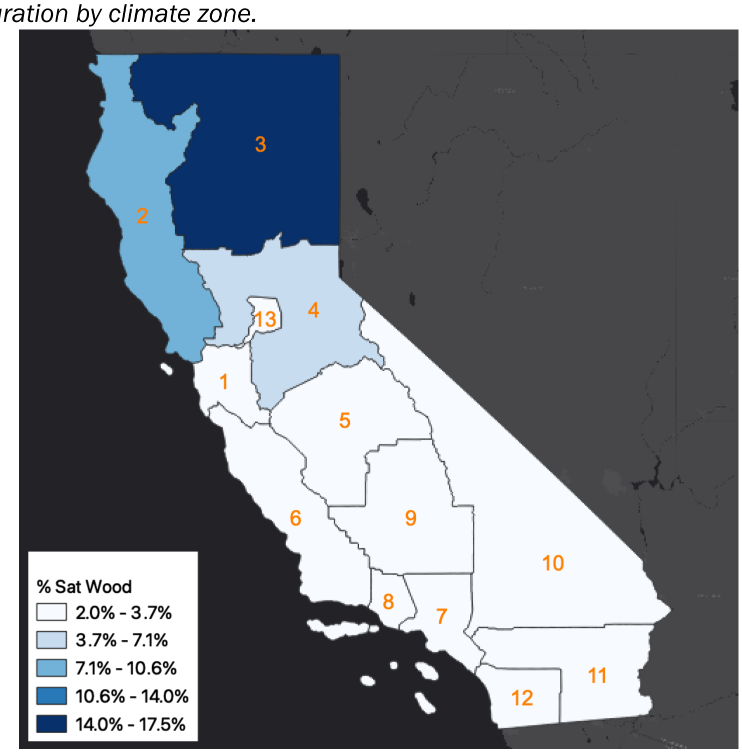

Figure 43: Wood saturation by climate zone.

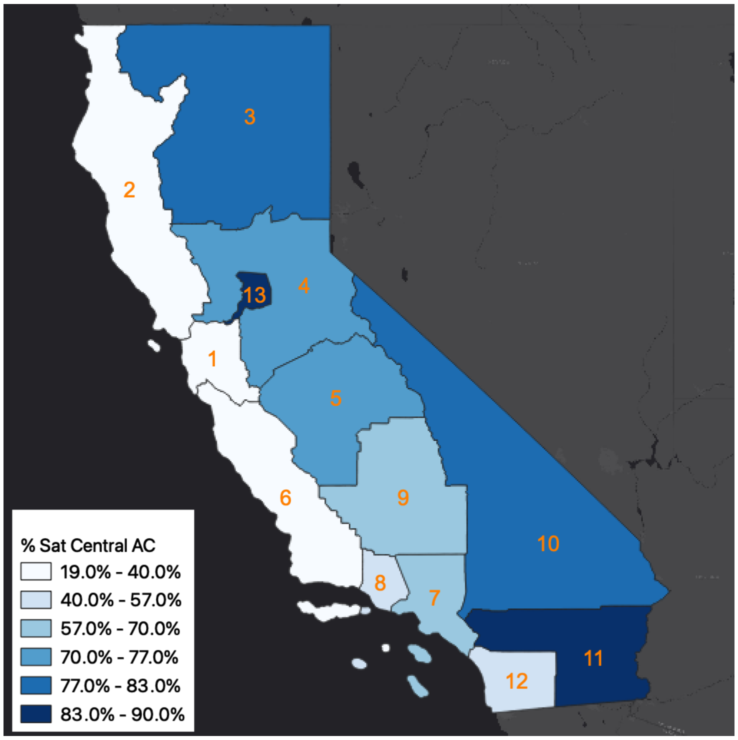

Figure 44: Central AC saturation by climate zone.

Appendix E: Technologies Glossary

Category 1: Housing Efficiency Upgrades

HVAC Measures

- Thermostatic Expansion Valves (TXVs): these valves regulate refrigerant flow to match load conditions, thus reducing compressor load within a central AC unit. ACs with TXVs operate 10% - 20% more efficiently [11].
- Programmable Thermostats: these thermostats reduce heating and cooling load by automatically changing the home's set point while it is not occupied [11].
- Ceiling Fans: ceiling fans can reduce set point requirements, because air motion can satisfy cooling needs without actually decreasing room temperature [11].
- Whole House Fans: these fans 1) pull air from outside and move it through the home and/or 2) remove hot air via the attic. Whole house fans can keep homes cool during the summer with about three times more efficiency than ACs [11].
- Attic Venting: attic fans can reduce attic heat gain in the summer and prevent attic condensation in the winter [11].
- HVAC Diagnostic Testing and Repair: this measure involves inspecting ACs and changing the refrigerant level, and possibly cleaning the coils, blowers, and filters. Furnace fan controls can also be adjusted to improve cycling efficiency [11].
- Duct Repair: duct leakage is a function of equipment quality, installation effectiveness, and duct age. Sealing tape and/or aerosols can be used to repair a leaking duct [11].
- Duct Insulation: existing ductwork can be insulated by wrapping the ducts with insulating material. Duct insulation inhibits heat transfer through the duct to the outside [11].

Building Envelope Measures

- Ceiling Insulation: this measures involves adding insulating material to the ceilings, inhibiting the flow of heat into or out of the home via the ceiling [11].
- Floor Insulation: this measures involves adding insulating material to raised floors, inhibiting the flow of heat into or out of the home via the floors [11].
- Wall Insulation: this measure involves adding insulation to un-insulated walls by drilling holes into the buildings and blowing in insulative material. Wall insulation similarly inhibits the flow of heat into or out of the home via the walls [11].
- Infiltration Reduction: this measure involves installing weatherstripping and caulking to improve building tightness and reduce leakage. Typically blower doors are used to identify large leaks, which are the most economical to fix [11].
- Cool Roofs: this measure involves using lighter-colored roofs such that the roof absorbs less solar radiation, reducing summer cooling load [11].
- Double Pane Clear Windows to Double Pane, Med Low-E Coating Windows: heat transfer through windows can be altered by changing the type of glass used, the number of panes, the solar transmittance, the gap thickness between panes, and the type of gas used in the gap. The best widows let solar light (short wavelength) through but reflect low wavelength heat from inside back into the room [11].
- Window Films or Sunscreens: this measure involves adding a dark colored film or screen to existing home windows, decreasing the amount of solar light let into the building, and therefore decreasing cooling load [11].

Water Heater Measures

- Low-Flow Showerhead: conventional showerheads use 3.5 - 6.0 gallons of water per minute, while low-flow showerheads use 1.0 - 2.5 gallons of water per minute. As showering typically accounts for 25% of residential hot water usage, low-flow showerheads can have high impact at low cost [11].

- Pipe Wrap: this measure involves wrapping the first five feet of pipe closest to the water heater with insulative material, reducing heat loss through the pipe [11].
- Faucet Aerators: aerators are threaded screens that attach to existing faucets. They reduce water flow by adding air bubbles into the water stream. Aerators can reduce water flow from 3-5 gallons per minute to 1-2 gallons per minute. Kitchen and bathroom sinks typically account for 7% of hot water energy use, and thus aerators can have high impact at low cost [11].
- Water Heater Blankets: this measure involves installing a fiberglass blanket on the outside of a water heater storage tank. The blanket reduces heat loss through the tank and therefore saves energy [11].

Category 2: Efficient Appliances

- Lighting: there are generally three types of indoor bulbs -- incandescent, compact fluorescent lamps (CFL), and LEDs. According to NREL's efficiency database [15], the rated efficiency of each of these bulbs are as follows: incandescent - 15 lm/W, CFL - 55 lm/W, and LED - 80 lm/W, where lm/W measures the amount of light (lm or lumens) produced in a given watt. Due to favorable economics, short lifespans, and stringent regulation, many homes have upgraded their bulbs in the last decade or two.
- NG Furnaces: condensing gas furnaces (about 90% efficient) are more efficient than standard NG furnaces (about 80% efficient). Condensing gas furnaces operate more efficiently by deriving useful heat from the vaporized by-products of combustion [11]. Even more efficient NG furnaces employ electronically commutated motors to slowly modulate (ramp up or down) in response to room temperature, as opposed to cycling on and off [13].
- NG Water Heaters: condensing NG water heaters operate more efficiently by deriving useful heat from the vaporized by-products of combustion [13]. Another efficient option is instantaneous (or tankless) water heaters -- these operate more efficiently by heating water as it is piped into the home, as opposed to heating an entire storage tank. Tankless water heaters have efficiencies between 90% (typical) and 97% (high) [13].
- NG Clothes Dryer: efficient clothes dryers use moisture-sensing devices to terminate the drying cycle rather than using a timer, increasing the efficiency of the process. In addition, an energy efficient motor is used for spinning [11].
- Central Air Conditioner: AC efficiency is a function of the quality of materials used in the machine, the size of the unit, the type of condenser used (air cooled or evaporatively cooled, the latter of which is located outdoors), and the system configuration (split systems include an outdoor condenser section and an indoor evaporation section connected by refrigerant lines, whereas unitary systems are installed all-together) [11].
- Room AC: efficiency improvements are attained by using higher efficiency compressors and fan motors, and by increasing the heat transfer area available in the evaporator and condenser (this can be done by using larger heat exchanges, finer fin spacing, micro channel heat exchangers, and more) [13].
- Refrigerators and Freezers: refrigerator efficiency can be improved by insulating the refrigerator cabinet, increasing the compressor efficiency, increasing the evaporator fan efficiency, employing defrost controls, using mullion heaters, using oversized condenser coils, and improving door seals. The DOE enacted refrigerator and freezer efficiency

standards in 1990, which has resulted in large improvements to refrigerator and freezer efficiencies [11].
- Clothes Washer: high efficiency clothes washers eliminate the warm rinse option and utilize spray mechanisms to rinse clothes. In addition, energy efficient clothes washers utilize a spin cycle that dries clothes more effectively, while doing so with higher efficiency motors [11].
- Dishwasher: energy efficient dishwashers use cooler water to clean dishes. They also use more effective washing actions, energy efficient motors, and sensors to determine the required wash cycle length and water temperature [11].

Category 3: Electric Appliances

- Air Source Heat Pumps: ASHPs move heat between indoor and outdoor air. Ducted ASHPs generate heating / cooling in a central location within the home, and then duct heating / cooling throughout the home. By comparison, ductless mini-split ASPHs pipe refrigerant to mini-heat-pump systems throughout the home, which generate heating / cooling in the rooms that need it. Mini-split ASHPs are slightly more efficient than ducted heat pumps due to mitigating ducting losses. AHSPs are amongst the cheaper space heat pump options, and thus are more popular within the US [16].
- Ground Source Heat Pumps: GSHPs use underground rock or groundwater as a heating reservoir. GSHPs are generally more efficient and reliable (less weather dependent), but are far more expensive due to drilling requirements during installation [16].
- Water Heat Pumps: come in two configurations: 1) an all-in-one design, in which the heat pump and storage components are integrated together, or 2) split systems, where the heat pump and storage components are separated [16].
- Solar Water Heaters, Direct vs Indirect: with direct configurations, water is pre-heated directly by solar rays, after which it is sent to what resembles a typical storage water heater (either gas or electric) for backup heating. By comparison, with indirect configurations, a heating fluid is heated by the solar rays, and then the heating fluid exchanges its heat with potable water within a heat exchanger. Direct solar water heaters are typically cheaper but are less reliable and robust than indirect solar water heaters [32].
- Solar Water Heaters, Passive vs Active (Thermosiphon): active solar water heaters rely on pumps and controls to move water, whereas the latter relies on natural buoyancy differences between hot and cold water. Thermosiphon configurations generally feature a large water tank installed on the roof above the solar water heater panel. Passive systems are generally more cost effective, but again are less reliable than active systems [32].
- Heat Pump Clothes Dryer: uses a vapor compression driven dehumidifier to condense water from circulated air within the clothes dryer. They use about 55% less energy than electric resistance dryers, however they typically take longer to dry clothes [16].
- Electric Induction Stoves: these heat food via electromagnetic fields rather than via radiant heat. Induction cooking represents the most expensive but most efficient electric cooking option [16].
- Convection Ovens: utilize a traditional heating element, but additionally use a fan to circulate air around the food.

Appendix F: Cost of Carbon Abatement by Climate Zone, Linear Regression Analysis

Figures 45 and 46 below explore the reasoning for behaviors seen in Figure 28. In Figures 45 and 46, a Climate Zone Metric is defined, in this case simply equal to the inverse of NG water heating energy intensity [21] for each climate zone. The Climate Zone Metric has a strong correlation with the cost of carbon abatement, meaning climate zones that require more water heating have a lower cost of carbon abatement. This is because in these climate zones, water heat pumps mitigate more NG combustion emissions while adding the same amount of F-Gas emissions (F-Gas emissions are assumed to be independent of equipment usage [6]).

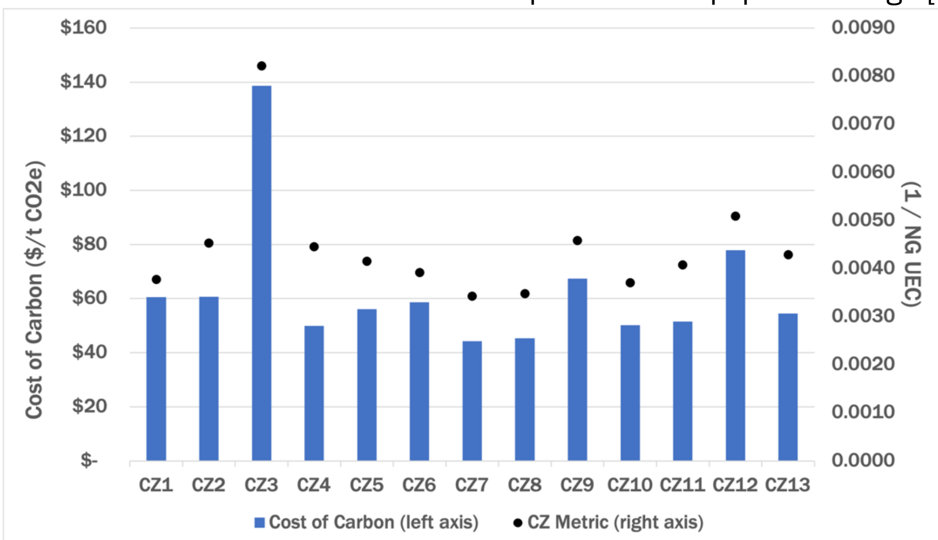

Figure 45: Exploring water heat pump's geographic dependency.

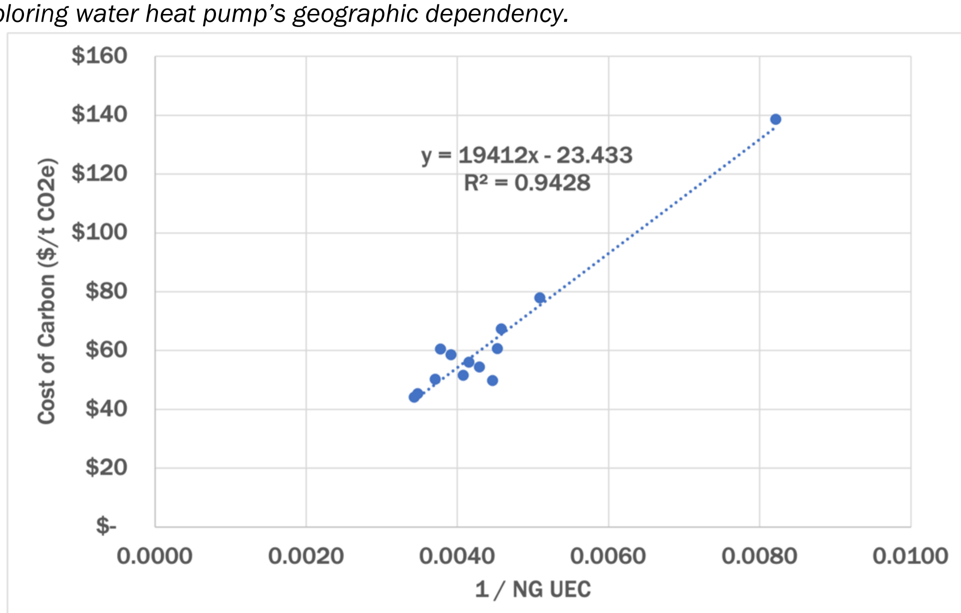

Figure 46: Exploring water heat pump's geographic dependency.

[21] Energy intensity = energy used per home per year

For space heat pumps, the relationship between cost of carbon abatement and climate zone is a bit more complex. Here the Climate Zone Metric is set equal to (1 / Space Heating Energy Intensity) × (% Saturation of NG Furnaces / % Saturation of Central ACs). There is a strong correlation between the Climate Zone Metric and the cost of carbon abatement. The Climate Zone Metric captures two simultaneous dependencies. The first term argues -- similar to water heat pumps -- that climate zones that require more heating will have a smaller cost of carbon abatement. Again, this is because in these climate zones, space heat pumps mitigate more NG combustion emissions while adding the same amount of F-Gas emissions. The second term argues that climate zones that have more ACs than NG furnaces will have a better cost of carbon abatement -- this is because in these climate zones, the economic and environmental benefits of AC scrapping is felt for a longer period of time (there are more ACs to scrap).

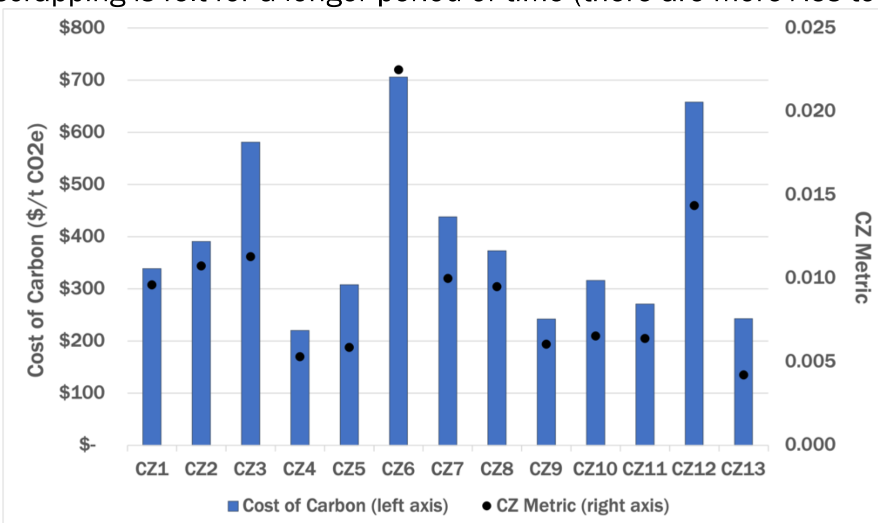

Figure 47: Exploring space heat pump's geographic dependency.

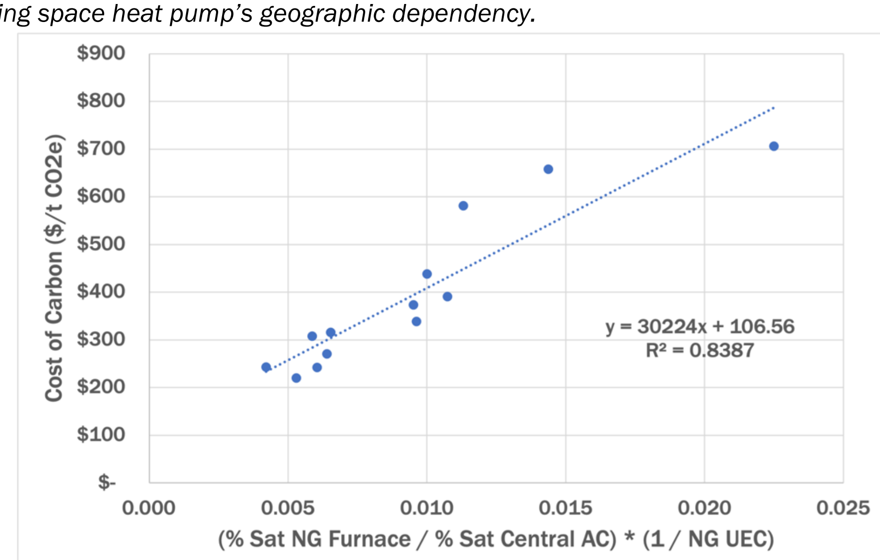

Figure 48: Exploring space heat pump's geographic dependency.

Appendix G: E3 Sensitivity Analyses

A sensitivity analysis was done utilizing E3's assumptions for commodity costs and heat pump efficiencies [7]. Assumptions are summarized below, with E3 notably forecasting increasing NG and electricity prices, and more aggressive space heat pump efficiencies compared to ResLEAP (Figures 49 - 52).

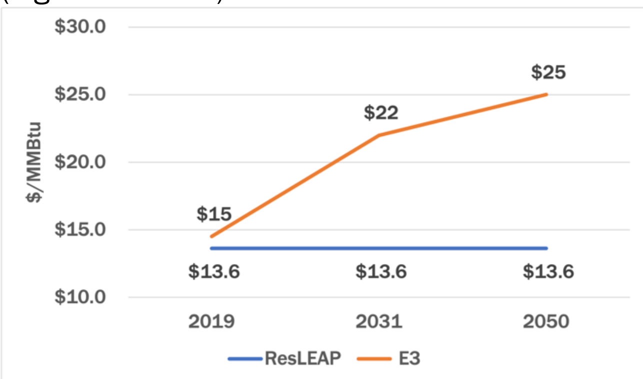

Figure 49: NG cost assumptions [7].

Figure 50: Electricity cost assumptions [7].

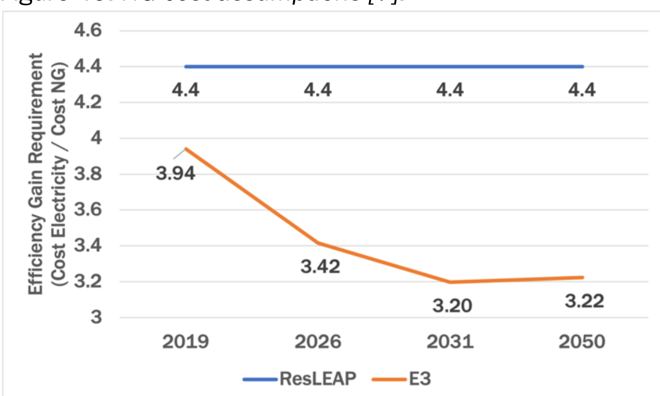

Figure 51: Efficiency gain requirement / electric premium [7].

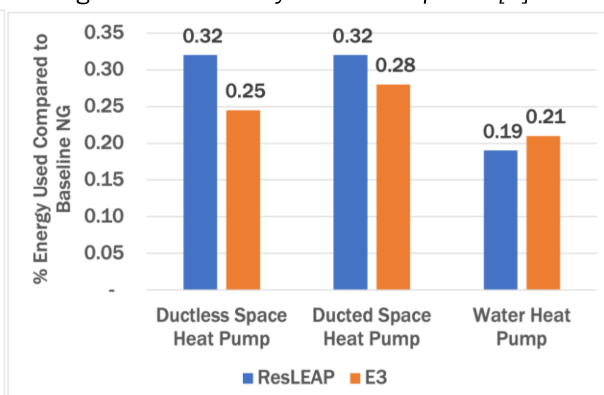

Figure 52: Efficiency assumptions [7].

E3's assumptions are plugged into ResLEAP, with results shown in Figure 53. In general, electric devices perform slightly better, due to electricity being closer in price to NG on an equal energy basis (Figure 51). Furthermore, with more aggressive space heat pump efficiency assumptions, space heat pumps produce modest fuel benefits as opposed to costs, resulting in an improved cost of carbon abatement.

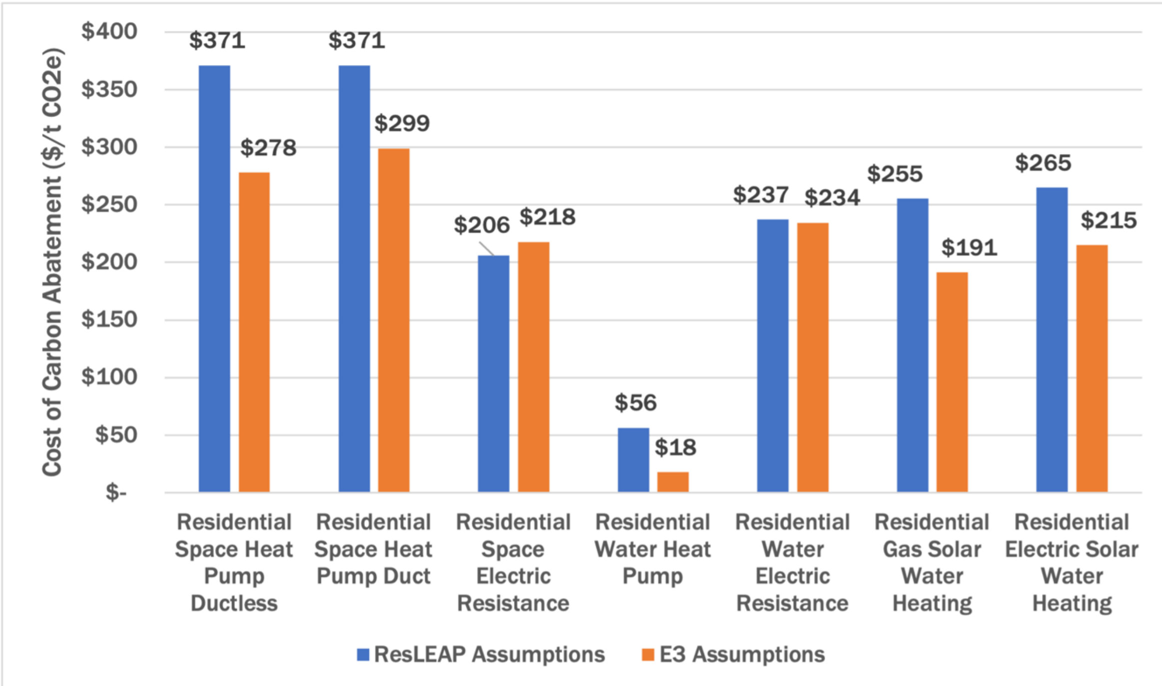

Figure 53: Space and water heating cost of carbon abatement, ResLEAP vs E3 Assumptions.

Appendix H: Decarbonize Residential, Grid Deltas

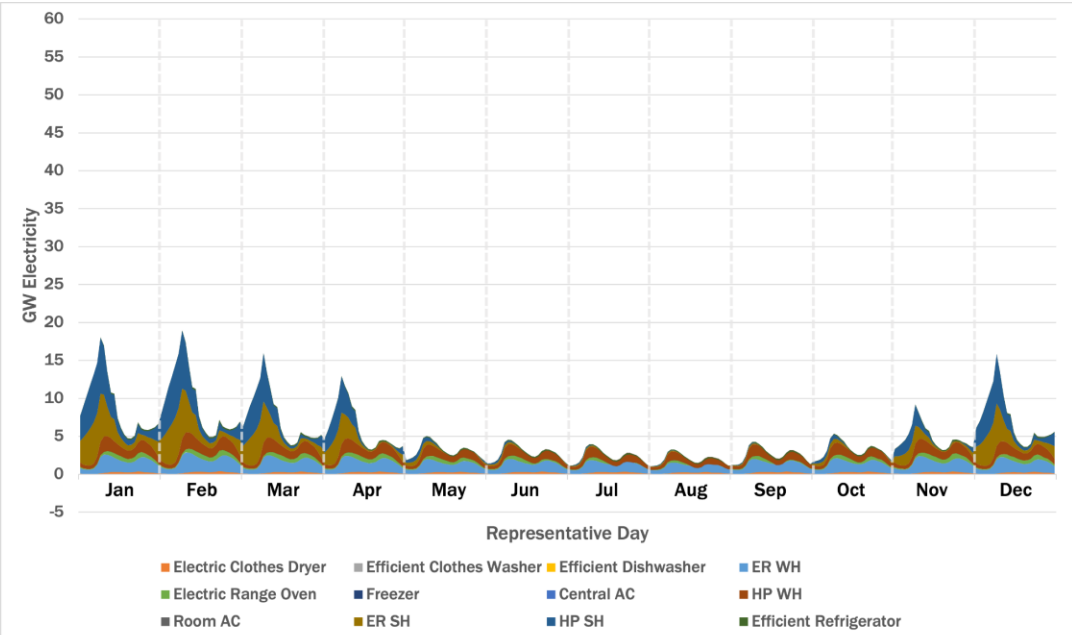

Figure 54: Decarbonize Residential 2045 load shape, difference from baseline.

Figure 54 emphasizes electricity deltas between the Decarbonize Residential scenario and the Baseline Scenario. Electric resistance heaters are responsible for the largest delta despite only serving 25% of the state's service needs. Electrified range ovens create a noticeable but mainly negligible change, while electric clothes dryers are not even detectable at the scale shown. Similarly, efficiency upgrades to ACs, freezers, clothes washers, and dishwashers do not lead to distinguishable improvements.

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