Heat Pump Controls: Decarbonizing Buildings While Avoiding Electric Resistance Heating and Higher Net Peak Demand

Jon McHugh, McHugh Energy
Alea German, Frontier Energy
Amy Dryden, Association for Energy Affordability
Ben Larson, Larson Energy Research
Dove Feng, TRC Companies
John Bade, 2050 Partners
Mark Alatorre, PG&E

ABSTRACT

California's Greenhouse Gas (GHG) goals include reduction of greenhouse gas emissions by 30% from 1990 levels by 2030 and GHG neutrality by 2045. The California renewable portfolio standard (RPS) requires a carbon free electrical grid by 2045. In the meantime, the electric grid is characterized by low GHG emissions during the middle of the day when the sun shines, and higher emissions at other times. Responding to state policy, energy efficiency standards and utility efficiency program offerings are increasingly promoting efficient all-electric or "decarbonized" buildings.

For residential space heating, efficient fuel switching from gas to electricity requires the use of heat pumps which have a Coefficient of Performance (COP) of 2+ as compared to a COP of 1 for electric resistance heating. Simulated energy use of residential heat pump space heating systems is often based on idealized design and operation. This paper has assembled measured data of heat pumps using more energy or Carbon than predicted by the idealized model of heat pump operation and has hypothesized the mechanisms of these additional impacts. These include:

- Behavioral preferences and thermostat schedules that increase loads from setpoint changes during high GHG electricity generation periods
- Excessive use of inefficient supplemental electric resistance heating due to undersized heat pump capacity and default use of resistance heating during changes in setpoint
- Unneeded electric resistance crankcase heating during periods when liquid refrigerant will not migrate to the compressor.

This paper is a call to action to address these efficiency problems so heat pump space heating systems will be living up to their technical promise.

Background

Each of the last four decades has been successively warmer than any decade going back to 1850. Global surface temperature in 21st century is 1 degree Celsius higher than 1850–1900. Global temperatures have not been this high in the last 6,500 years. Almost all of this temperature rise is attributed to increases in greenhouse gases due to human activities. The greenhouse gases with greatest effect on temperature increases are Carbon dioxide, and methane. With increased global temperatures, come increased severity of heat events, droughts, and floods. Limiting human-induced global warming to a specific level requires limiting cumulative

CO2 emissions. Ultimately this requires approaching net zero CO2 emissions, along with rapid reductions in other greenhouse gas emissions, especially methane. To limit global temperature rise, the IPCC (2018) has recommended a GHG reduction scenario where global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 and reach net zero around 2050 and non-CO_2 (methane, black carbon, and nitrous oxides) emissions are cut in half. Reducing non-CO_2 greenhouse gas emissions has the side benefit of improving air quality and reducing the prevalence of diseases associated with air pollution.

California GHG Policy and Decarbonization of the Electric Grid

The state of California is attempting to "follow the science" on global warming and pursuing the IPCC's recommendations. California's The Global Warming Solutions Act of 2006 (AB32), limited GHGs in the state to 1990 levels by 2020. However, this was not sufficient to address the climate crisis. Executive orders c all for reducing annual emissions of GHGs to 40% below 2020 emissions levels by 2030, and for the state to be carbon neutral by 2045. (CARB 2022) Additional legislation (SB 1383, 2016) requires the following emission reductions below 2013 levels by 2030 for the following non-CO2 GHGs: methane (40%), hydrofluorocarbon gases (40%), and anthropogenic black carbon (50%). The electric grid is becoming increasingly decarbonized: Senate Bill 100 requires that by renewable energy sources provide 44% of electricity by 2024, 52% by 2027 and 60% by 2030. By 2045, all the state's electricity is required to come from carbon-free resources.

In California most renewable generation is from solar photovoltaics[1]. As shown in Figure 1, the "net load" served by "all other" non-renewable resources is found by subtracting renewable energy generation from the gross load. In the Winter both the gross and net load have peaks in the early morning and early evening.

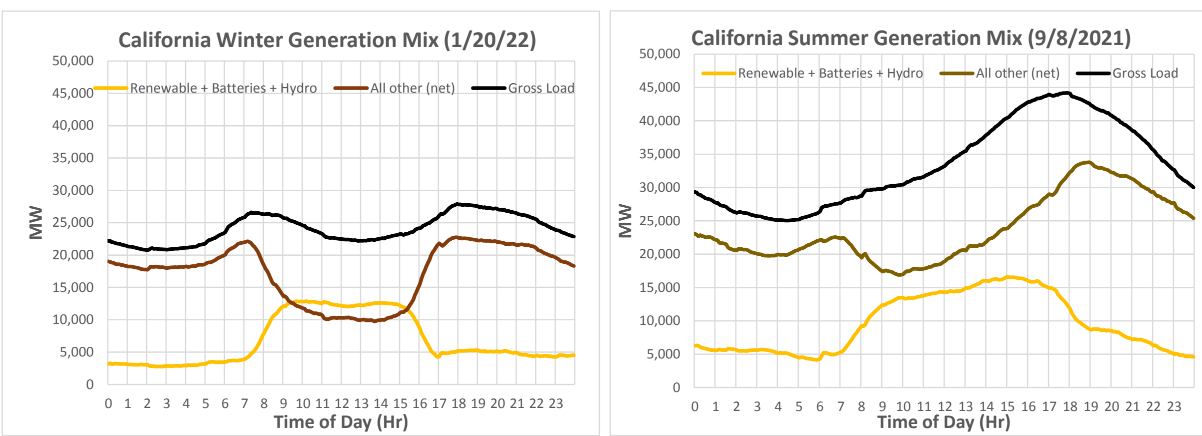


Figure 1. California Generation Mix Winter and Hot Summer Day (CalISO, 2022)

Figure 2 summarizes the hourly GHG emission factors developed for the 2022 Title 24 standards. The details on how these emissions factors are calculated can be found in the Time Dependent Valuation Methodology report (E3 2020) along with the methodology used to calculate life cycle cost and source energy of energy used by buildings. This methodology

[1] Renewable used here includes renewables, storage, and hydro

accounts for the major emissions resulting from combustion of fuels to generate electricity at a power plant or to generate heat on site in a gas-fired furnace or water heater.

Res 30 yr Elec lb CO2e/kWh

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0.668	0.615	0.399	0.225	0.190	0.273	0.514	0.593	0.569	0.557	0.572	0.610
1	0.656	0.608	0.395	0.225	0.190	0.270	0.513	0.590	0.560	0.552	0.558	0.595
2	0.649	0.605	0.393	0.224	0.190	0.270	0.513	0.589	0.552	0.550	0.547	0.586
3	0.651	0.605	0.394	0.225	0.190	0.270	0.513	0.590	0.552	0.552	0.545	0.586
4	0.663	0.612	0.398	0.226	0.190	0.270	0.515	0.592	0.559	0.558	0.552	0.598
5	0.675	0.621	0.402	0.227	0.190	0.265	0.515	0.595	0.569	0.564	0.568	0.617
6	0.681	0.623	0.403	0.208	0.096	0.111	0.417	0.548	0.542	0.564	0.579	0.628
7	0.677	0.607	0.232	0.047	0.013	0.029	0.169	0.268	0.231	0.318	0.464	0.613
8	0.479	0.263	0.058	0.005	0.003	0.016	0.078	0.097	0.057	0.079	0.175	0.381
9	0.312	0.130	0.031	0.001	0.001	0.014	0.051	0.071	0.039	0.057	0.136	0.276
10	0.281	0.117	0.028	0.000	0.000	0.013	0.049	0.070	0.038	0.052	0.133	0.252
11	0.275	0.112	0.028	0.000	0.001	0.012	0.046	0.067	0.033	0.050	0.131	0.240
12	0.273	0.108	0.028	0.000	0.000	0.013	0.048	0.068	0.041	0.051	0.130	0.234
13	0.276	0.112	0.028	0.000	0.000	0.013	0.049	0.069	0.042	0.053	0.134	0.247
14	0.289	0.118	0.029	0.000	0.001	0.015	0.052	0.073	0.052	0.060	0.147	0.262
15	0.323	0.129	0.036	0.000	0.005	0.023	0.067	0.097	0.093	0.100	0.210	0.315
16	0.582	0.263	0.112	0.012	0.029	0.071	0.138	0.207	0.251	0.461	0.590	0.648
17	0.703	0.635	0.401	0.200	0.150	0.205	0.344	0.572	0.615	0.587	0.598	0.650
18	0.703	0.636	0.409	0.240	0.235	0.364	0.602	0.670	0.626	0.586	0.598	0.650
19	0.703	0.636	0.410	0.240	0.234	0.397	0.604	0.652	0.609	0.588	0.598	0.650
20	0.706	0.638	0.410	0.239	0.228	0.348	0.576	0.641	0.603	0.587	0.601	0.653
21	0.705	0.638	0.403	0.231	0.213	0.317	0.543	0.614	0.587	0.573	0.600	0.651
22	0.688	0.624	0.399	0.228	0.204	0.296	0.524	0.604	0.581	0.569	0.587	0.634
23	0.683	0.621	0.397	0.227	0.202	0.286	0.520	0.600	0.576	0.566	0.579	0.625

Figure 2. Average Hourly GHG Emission Factor by Month (lb. CO2e/kWh) Source: (CEC, 2020)

The lowest cost renewable energy sources in California are solar photovoltaic systems that track closely the solar irradiance from sunlight (more near solar noon than in the morning or evening and more hours of production in the summer than the winter). When evaluated over a 30-year time period this has several repercussions:

- The marginal cost for electricity in the middle of the day is low
- The marginal carbon emissions per kWh varies dramatically by time of day and time of year with lower emissions in the middle of the day
- On average California electricity grid is relatively low carbon with an unweighted average carbon emissions factor of 0.343 lbs. CO_2e/kWh

In comparison, the carbon emission factors for natural gas usage are unchanged for all hours for all months and has a value of 0.129 lbs. CO_2e /kBtu (0.440 lbs. CO_2e /kWh). One might think that this difference between electricity and natural gas is not that much. However, converting natural gas into heat has a thermal efficiency of around 80% for non-condensing equipment or 90% for condensing equipment. However, the worst thermal conversion efficiency is electric resistance heating at 100% efficiency, but heat pump space heating can do much better with a COP (coefficient of performance) of 200% to 350%.

As described earlier, California policy is to have a carbon free grid by 2045. There are efforts to reduce the carbon content of natural gas, primarily by capturing methane in landfills and feedlots and mixing with the natural gas derived from oil wells. However, the availability of methane available for capture from these sources is limited. The National Renewable Energy Laboratory (NREL 2013) estimates that the methane technical potential from landfill material, animal manure, wastewater, and industrial, institutional, and commercial organic waste in the US is approximately equivalent to 420 Billion cubic feet per year. The Energy Information Administration (EIA 2022) estimates that in 2021 the US annual natural gas consumption was approximately 30 Trillion cubic feet per year. Thus, the technical potential for renewable natural gas is around 1.4% of total natural gas consumption. As a result, the long-term reduction in natural gas emissions does not look promising. This impacts natural gas used in combustion on site and natural gas used to generate electricity.

California Decarbonization of Space Heating with Heat Pumps

Given this background, the state of California has been increasingly looking towards electrification of heating end-uses as one of the key strategies to decarbonize the operation of buildings and industrial processes. Heat pump space heating is seen as the most effective ways to reduce the carbon footprint of space heating. Heap pumps use relatively low GHG electricity, and they are two to three times more efficient than electric resistance heating.

In California, the market share of electric space heating has been relatively small but growing. In the 2003 California Statewide Residential Appliance Saturation Study (RASS) 7.6% of residential (single family and multifamily) construction used electric heating but by the 2019 RASS, this market share had grown to 21.2%. Over the same period the share of heat pumps grew from 0.8% to 4.0% -- an increase of 400%.

This growth in heat pump use will be accelerated by heat pump space heating requirements in the 2022 version of the California energy code. Single family homes will be prescriptively required to use heat pump space heating in climate zones 3, 4, 13 and 14 [§150.1(c)6]; this accounts for approximately 15,000 new homes per year or approximately 26% of all new single family construction. Similarly heat pumps are required for space heating of dwelling units in climate zones 1-15 in low rise multifamily and climate zones 2-16 in high rise multifamily buildings [2022 Title 24, part 6 §170.2(c)3A]; this accounts for approximately 51,500 new dwelling units per year or approximately 99% of all new multifamily construction. Heat pump space heating will be the new performance baseline for these climate zones. This is but the start; in the Integrated Energy Policy Report (CEC 2002), "the CEC is recommending a goal of installing at least six million heat pumps in new and existing buildings by 2030."

Problem Statement

This paper identifies areas where the actual energy consumption of heat pump space heating or GHG emission associated with heat pump space heating is higher than its ideal operation in the following areas:

- Use of supplemental electric resistance heating during changes in setpoint or when it is cold outside
- Scheduling of heat pump thermostat settings that result in consumption during high GHG electricity generation periods
- Unnecessary use of crankcase heating (i.e., compressor conditions are such that liquid refrigerant will not migrate to the compressor).

Heat pump load profile – coincident with peak

The typical load profile for space heating is bimodal with a large peak in the morning around 6 am and a smaller peak around 4 pm. These peaks represent the pull up loads associated with setpoint changes around when people wake up and a smaller peak from a smaller fraction of people who have turned off or setback their thermostat while away for work and are now warming up the house for the evening. The morning heating load is also larger because ambient temperatures are typically lower in the early morning. Figure 3 shows the metered, average hourly energy consumption of ten heat pumps for all days in January. Note that upper red bar represents the energy consumption of the indoor unit and includes the energy consumption of inefficient auxiliary resistance heating. The use of auxiliary heating exacerbates the morning electrical peak. The colored background to the graph represents the GHG emissions factors. These two peaks occur at times when the solar resource is not available and thus, they are at times when primarily gas generation is serving the load and emission factors are higher. With the state of California embarking on a major increase in the use of heat pumps for heating, this load will likely increase the net winter peaks seen by the CalISO (California Independent System Operator) electrical grid as were shown in Figure 1.

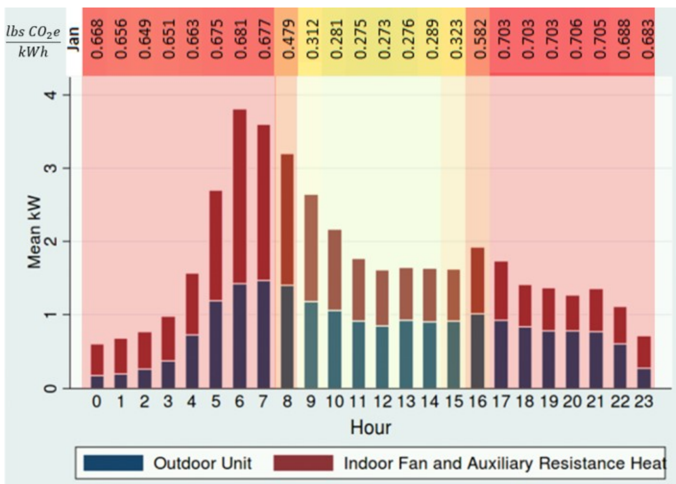


Figure 3. Monitored Heat Pump Operation – Average of ten heat Pumps Overlayed on California Long Run Marginal GHG Emission Factors for January. Source: Ecotope 2014

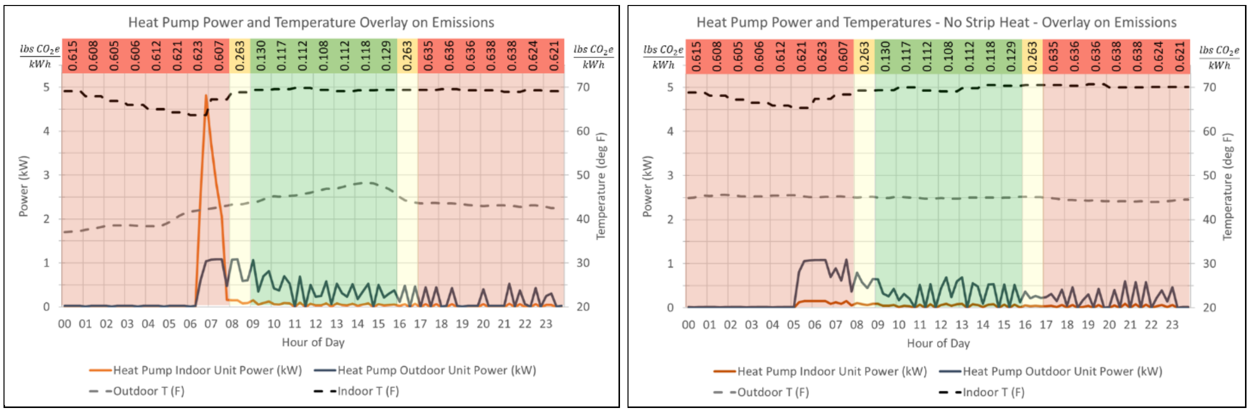
Heat pump output capacity (sizing)

The output capacity of a heat pump has a direct impact on how much electric resistance heating is used. As outdoor temperatures drop, so does the ability of heat pumps to move heat from outside to inside. Precisely when the building needs heat the most, the heat pump is most challenged to provide it. A widespread practice to address this need is to install electric resistance elements as auxiliary heating (BPA 2019). The resistance elements draw a disproportionate amount of electrical power when they run which can place high demand on the transmission, distribution, and electrical supply system. The resistance elements are far less efficient than the heat pump system so energy usage increases (and potentially GHG emissions) during these periods. The larger the output capacity of the heat pump is, however, the more heat it can provide, especially at colder air temperatures and the less the resistance elements are needed.

Heat pump capacity is more expensive than resistance elements so a traditional way to install a system is to size the heat pump to provide most of the heat for the season while relying on auxiliary resistance heat for the colder periods. This reduces the first cost, but the installed heat pump size will be smaller than the optimum for minimizing life cycle cost. Often the heat pump is inadequately sized, and the heating system relies on resistance heating for too many hours which brings down the annual average operating system COP (Baylon 2005).

Heat pump change in setpoint – often engages auxiliary heating

Resistance heating shows up in heat pump systems not only due to inadequate compressor output capacity at lower temperatures but also in response to thermostat setpoint changes. If occupants program the thermostat with a nighttime setback and a morning recovery, a setpoint increase from 64F to 70F can trigger resistance heat (Ecotope 2014, Larson 2010). Figure 4(a) and Figure 4(b), sourced from metered data, illustrate the differences in setback recovery energy use between uncontrolled and controlled resistance heat.



a) With supplemental heating b) Without supplemental heating

Figure 4. Monitored Heat Pump Operation with and without Supplemental Resistance Heat During Recovery from Setback Overlayed on California Long Run Marginal GHG Emission Factors for February. HP data source (Ecotope 2014)

The house in Figure 4(a) is setback to ~64^{0}F overnight (Indoor TD) and experiences outdoor temperatures in the upper thirties ^{0}F overnight (Outdoor TDT). At 6:30AM, the thermostat is scheduled to warm the house up to ~70^{0}F. The system does so by turning on both the heat pump (Heat Pump Outdoor Unit at 1 kW) and the auxiliary electric resistance elements (Heat Pump Indoor Unit at 5 kW). In contrast is Figure 4(b), featuring the same house, on a different day, but with controlled resistance heat. There is a similar setback to ~65^{0}F overnight. At 5AM in the morning, the heat pump, using no resistance heat starts to warm the house to ~70^{0}F. In Figure 4(b), the outdoor temperature is 45^{0}F and the system is configured such that electric resistance elements are locked out from running when the outdoor temperature is above 40^{0}F. Note that the recovery rate in Figure 4(b) is slower and setback is release an hour earlier but is up to temperature by 8 am while using less energy during setpoint recovery.

Both Figures 4(a) and 4(b) are overlayed on top of the California February GHG emissions factors for February. This illustrates not only the energy impact of using resistance heat but the also the GHG penalty. Similar to Figure 3, the resistance heat peak occurs during higher emission periods. Given current emissions schedules, morning warm-up will inevitably occur during higher periods, but the amount can clearly be exacerbated by the uncontrolled, inefficient resistance supplemental heat.

The exact amount and timing of resistance heat will depend most importantly on the thermostat controls but also secondarily on several factors including outdoor temperature, house heat loss rate, and house thermal mass. In one scenario, the thermostat may be configured to engage the compressor as the first stage. Then, after a giving time interval if the temperature has not risen enough, the thermostat may turn on resistance elements as the second stage. In other scenarios, the thermostat may immediately call for compressor and resistance heat simultaneously or stage on fractional amounts of the total resistance heat capacity more slowly.

Heat pump crankcase heater loads can be significant

If the compressor in a heat pump or air conditioning system colder than the other system components (condenser, evaporator, and related refrigerant lines) refrigerant may accumulate and condense in the bottom of the compressor. This is undesirable as the liquid refrigerant may mix with the compressor oil or sink to the bottom of the compressor sump. In either case, when the compressor turns on this may case the oil to foam and be swept out of the compressor causing a loss of lubricating oil in the compressor and too much oil in other system components which reduces their heat transfer capability. Liquid refrigerant and oil mixture entering in the compressor harms the compressor due to the incompressible nature of liquids and the high pressures that result. Heat pump, because they operate during cold periods, often have crankcase heaters. The crankcase heater heats any refrigerant in the compressor, so it stays in gaseous from and does not mix with the compressor oil. The crankcase heater needs to be operating when the compressor is off and maintain higher compressor temperatures than the evaporator.

Common modes of crankcase heater control can be any of the following or in combination.

- No control: crankcase heater is on anytime the heat pump is connected to power – even when thermostat is in off position
- Positive temperature coefficient (PTC) heater: as the heater gets hotter, the resistance increases and power declines, however turndown may be limited
- Linked to compressor liquid line pump down solenoid or compressor relay: crankcase heater off when compressor on
- Thermostatic control: crankcase heater off whenever ambient temperature above some fixed temperature, or differential temperature between the compressor and ambient temperature.

The use of crankcase heaters varies by manufacturers, compressor technology, size of system, length of piping and if product is intended for cold climate operation. Presence of the crankcase heater or which control scheme is being use is not always clear. There are also multiple ways of heating the crankcase. Some of the simplest methods of delivering heat to the crankcase is to have an immersion heater in sump of the crankcase or a resistance heater strapped on to the bottom of the crankcase (bellyband). Less evident crankcase heating circuits bypass the start capacitor in a capacitor start motor and run currently through the windings of the motor to generate heat; a similar approach is also being applied to inverter driven variable speed compressors. (Emerson 2021)

The power consumption of a crankcase heater does not affect SEER and EER ratings as it is not included in the testing protocols. However, heat pump off-cycle average power draw is not supposed to exceed more than 33 Watts per compressor.[2] This parasitic load can be quite significant. Compressor usage has been documented to go up when heat is not needed to offset crankcase heater heat. Crankcase heaters can use anywhere from 30 Watts to 100 Watts.

This usage is not calculated into energy consumption data. For one monitored project, total annual energy (heating/cooling as well as parasitic loads) averaged from 2.5 to 6.4 kWh/day by apartment. Cooling and heating energy made up roughly 24 percent and 20 percent of the

[2] Code of Federal Regulation 10 CFR §430.32(c).

totals, respectively, and baseloads of crankcase heaters, control boards, and reversing valves accounted for 45 percent of the total HVAC load on an annual basis (50 percent of heat pump energy). Since electrical metering was for the entire condensing (outdoor) unit, it was not possible to identify the actual distribution of baseload consumption between the crankcase, inverter controls, and the reversing valve. The crankcase heater was not listed in parts and was only noted in the installation wiring diagram. Figure 5 shows that for one multifamily complex, all the apartments regardless of their size and time of year, had fixed loads of around 100 watts (100 W x 24 hr = 2.4 kWh/day). Most of this load is predicted to be from uncontrolled crankcase heaters. (Dryden et al. 2021)

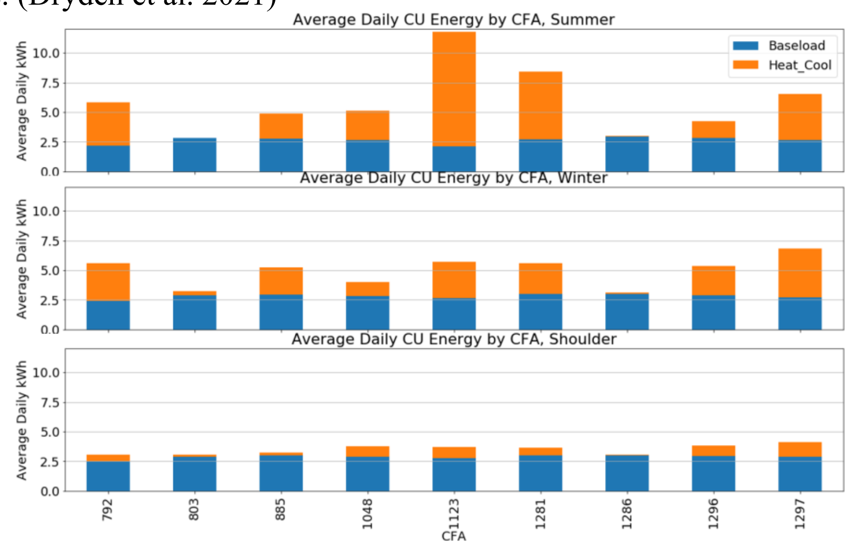


Figure 5. Monitored Heat Pump Condensing Unit Operation, isolating fixed loads (blue) from variable loads (orange) for split system ducted heat pumps for apartments with different conditioned floor area (CFA), by different times of year (summer, winter and shoulder months).

The Central Valley Research Home (CVRH) Project contains extensively monitored test homes in Stockton California. Crankcase heater control operation varied widely. Figure 6 illustrates the draw cycle of one system where the 30 Watt crankcase heater power draw was activated after two hours of compressor non-operation (see the gap between compressor cycling and crankcase heat in the figure). For this project, the heat pump only served the downstairs of the home and operated approximately 7 hours during the afternoon and evening. The crankcase heater would then turn on 2 hours after the last compressor cycle and remain for approximately 15 hours until the next afternoon's call for cooling. Adding both the crankcase heat and the standby energy use equated to roughly half the total energy for the downstairs cooling energy use. (Wilcox, et al. 2018)

Another home on the CVRH site contained two ducted variable capacity systems from the same manufacturer. The smaller system was a 1 ton variable capacity system and the larger system was a 1.5 ton variable capacity system in the same product line. Crankcase heat was observed in both system operations and was higher during the cooling season. The 1.5 ton system consumed a seasonal 34 kWh during cooling and 11 kWh during heating, while the 1 ton used 14 kWh of crankcase heat only during the cooling season. It is surprising that the 1 ton system did not use crankcase heating at all in the winter when one would expect crankcase heating is most needed to prevent damage to the compressor.

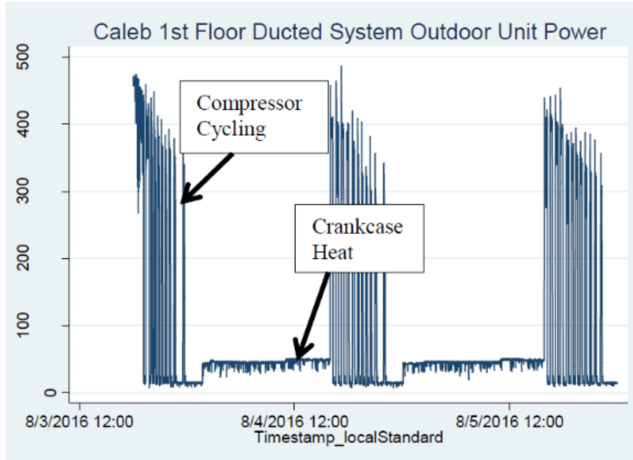


Figure 6. Crankcase heat constant draw after two hours of non-compressor operation. (Wilcox, Conant, and Chitwood 2018)

The slopes of the curves in Figure 7 seem to indicate that the crankcase heater control is working in the same manner as described in the earlier Wilcox, et al. (2018) paper. Crankcase heater consumption is proportional to how long the compressor is not operating. When in heating mode, the crankcase heater is operating more when it is warmer outside and there is little call for heating. Similarly, when in cooling mode, the crankcase heater is operating more when it is cooler outside and there is no call for cooling. As described earlier, there are many moderate and hot temperature hours of the year when the crankcase heater would be operating unnecessarily.

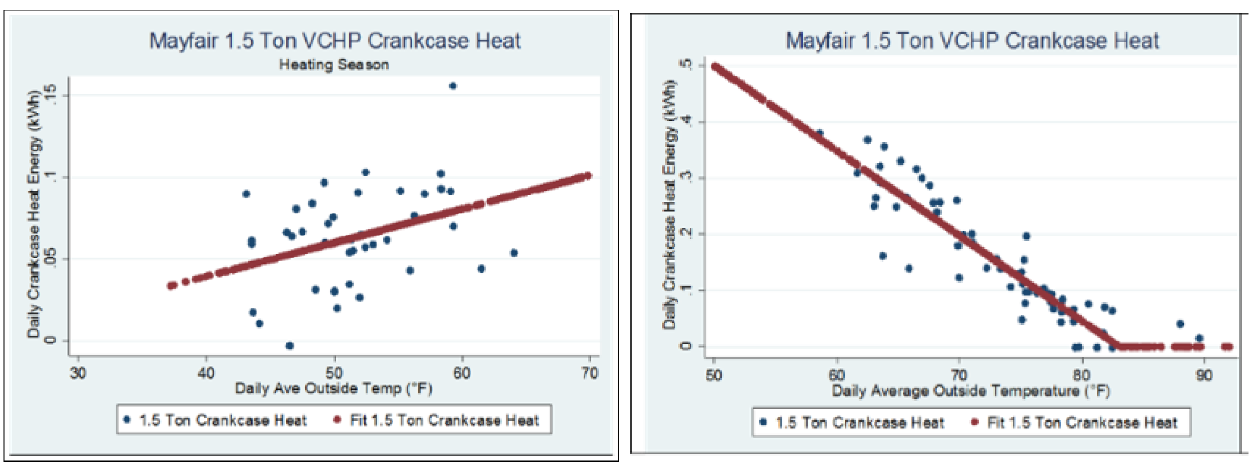


Figure 7. Crankcase heat energy use during heating and cooling. (Wilcox, Conant, and Chitwood 2018)

Energy Efficiency Codes and Standards Gaps

Thermostat specification in energy code ineffective in preventing unnecessary use of supplementary resistance heat

California's Title 24 part 6, energy code (Energy Code) has the following requirement for heat pump thermostats in section 110.2(b), which can be traced back to at least the 2005 version of the Energy Code. The requirement was written for single stage heat pump systems with electric resistance supplemental heat.

*(b) **Controls for Heat Pumps with Supplementary Electric Resistance Heaters.** Heat pumps with supplementary electric resistance heaters shall have controls:*

1. That prevent supplementary heater operation when the heating load can be met by the heat pump alone; and

2. In which the cut-on temperature for compression heating is higher than the cut-on temperature for supplementary heating, and the cut-off temperature for compression heating is higher than the cut-off temperature for supplementary heating.

***EXCEPTION 1 to Section 110.2(b):** The controls may allow supplementary heater operation during:*

A. Defrost; and

B. Transient periods such as start-ups and following room thermostat setpoint advance, if the controls provide preferential rate control, intelligent recovery, staging, ramping or another control mechanism designed to preclude the unnecessary operation of supplementary heating.

These requirements were designed to avoid or minimize the use of auxiliary or supplemental electric resistance heating. However, the lack of specificity hinders enforcing these requirements as specification; these include:

- When there is a change in setpoint, heating load (Btu/hr) is both the load to offset steady state heat loss from the space but also the “pull-up load” for temperature recovery. The faster the desired heat recovery, the higher the pull up load.
- Describing that the cut-on and cut-out temperatures of the heat pump system are higher than the supplemental heating system are helpful, but ultimately not enforceable since there is no description of how many degrees higher. If I setback (lower) my heat pump setpoint by 5 degrees every night and the heat pump cut-on temperatures is 2 degrees higher than the supplemental heat cut-on temperature, supplemental heating will be engaged each morning as setback is being released.
- Exception 1B. is similarly ambiguous about the “smart control” features that allow supplementary heating. How much time will the thermostat advance turning on the heat pump so that the space is up to temperature by the desired schedule? This language is intended to not stifle innovation but in doing so it omits criteria that provide a basis for enforcement.

Sizing requirements in Energy Code not designed to limit Supplementary Heating

California’s Energy Code requires that building heating and cooling loads be determined using industry standard methods including ASHRAE, SMACNA Residential Comfort System Installation Standards Manual, and ACCA Manual J. California Title 24, Part 11 green building standards code (CALGreen) also requires that heating and cooling equipment be selected according to ACCA Manual S or equivalent methods. Manual S dictates that heat pumps are selected based on the cooling load requirement to prevent oversized fixed capacity air conditioners being installed which results in excessive cycling and inefficient cooling operation. But allows heat pump system sizing up to 125% of the cooling capacity if larger heating capacity is required. Where the selected heat pump does not have sufficient capacity to supply the design heating load then electric resistance backup is sized for that difference.

In cold climates the Manual S sizing approach is not optimal for heating operation and will result in unnecessary electric resistance operation. Currently there is no enforcement mechanism for verifying heat pump equipment sizing and oversizing supplemental heat capacity will maintain comfort but with inefficient resistance heating that is costly to operate.

Appliance Efficiency Ratings Crankcase Heater Controls Shortcomings

The cooling efficiency of residential heat pumps are rated in terms of their Seasonal Energy Efficiency Ratio (SEER) and the heating efficiency is rated in terms of their Heating Seasonal Performance Factor (HSPF). Though both annual cooling efficiency and heating efficiency can be impacted significantly by crankcase heater energy consumption, neither of these ratings are impacted crankcase usage unless the crankcase heater is on when the compressor is operating [See 10 CFR part 430, subpart B, Appendix M]. However, heat pumps are required to be tested for their average off mode power consumption and to keep this below 33 Watts per compressor [see 10 CFR 430.32(c)6]. The calculation method for off-model power consumption includes correction factors for variable capacity compressors and cooling capacities over 36 kBtu/hr that obscure the true power in the off mode. The temperature conditions for the test do not exercise the crankcase heater through the full range of expected heat pump and air conditioning operating conditions. At this point in time the manufacturers are not required to disclose the control strategy or the crankcase heater wattage and there is not a clearly defined annual calculation or annual efficiency metric that accounts for crankcase heater use.

Performance Approach Energy Simulation Gaps

Simulation models are used to understand energy impacts of heat pumps and can be a powerful tool to evaluate scenarios and inform decisions from design to policy. However, the many assumptions in the models impact their accuracy. In California compliance with the energy code for new residential buildings is largely met using the whole building energy performance approach. This approach is based on using the California Simulation Engine (cse) to demonstrate that the proposed building uses less source energy and costs less operational energy than a minimally code compliant building.

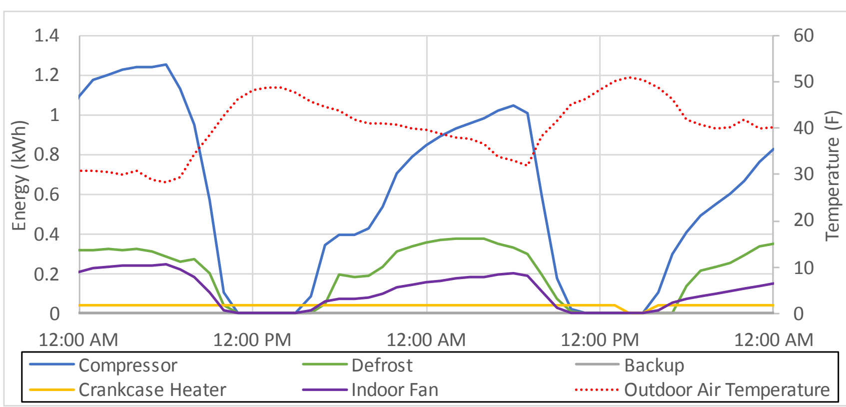


Figure 8. Heating system energy use in January for Sacramento, CA based on the cse energy model.

Key assumptions that impact heat pump energy performance are often unknown for a particular house, but are built-in as defaults in cse. These defaults include: thermostat schedule, system sizing, and operation of auxiliary systems including crankcase heating and defrost. In cse, the heating thermostat schedule for heat pumps is a constant setpoint of 68°F. This is meant to represent ideal thermostat operation by the occupant to minimize electric resistance backup needs. For occupants that setback their thermostats while in heating mode, the models will underestimate backup heating during the setpoint change at the end of the setback period. In some cases, the difference can be significant.

Figure 8 shows hourly energy use for a right-sized heat pump model in Sacramento, CA for two days in January from cse. The smooth profiles differ from the monitored data in Figures 4 and 5, which is typical for energy model data output at hourly timesteps.

Figure 9 shows daily energy use for the same model across the heating system relative to average daily temperature. This model estimates that compressor energy use comprises 65-70% of total heating energy use, electric resistance operation during defrost cycles represents 15-20%, and crankcase heater contributes ~5%. Backup heating is estimated to be negligible. This can be true even in the coldest California climates for new homes with right-sized heat pumps, thermostatic controls that lock out auxiliary heating, and improved crankcase heater control (see the next section). Roughly one quarter of total annual heating use is due to defrost and crankcase heater controls. The model assumes that the crankcase heater draws 40 Watts and operates anytime the outdoor dry bulb temperature is less than 50°F. The outdoor unit is assumed to go into defrost cycle whenever the outdoor temperature is between 17°F and 35°F. While these are reasonable assumptions for an ideal system, more robust equipment specific data is needed to better inform industry models and incent systems with energy conserving controls. It is likely electric resistance backup heating and crankcase heating is underestimated. Collecting thermostat schedules for heat pumps and equipment operational data is needed to improve models and revise codes to ensure that unnecessary energy use is reduced or eliminated.

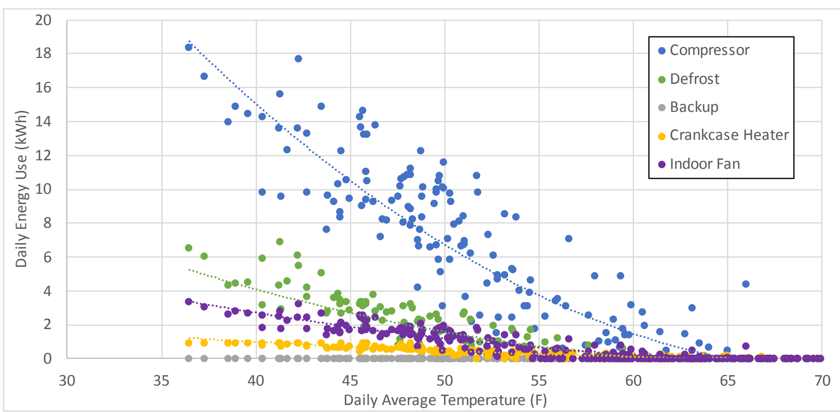


Figure 9. Daily heating system energy use relative to average daily temperature for Sacramento, CA based on the cse energy model.

Technological Solutions

Sizing and capacity to displace resistance heating

Limiting resistance heating is based firstly on adequate heat pump size and then improved sequence of operation for controls. The Bonneville Power Administration offers an efficiency program called Performance Tested Comfort Systems® (PTCS) which requires heat pump systems be sized to a balance point of 30 ^{0}F or less (Bonneville Power Administration 2017). That is, the heat pump compressor must be capable of heating the entire house when the outdoor temperature is above 30 ^{0}F. Below that temperature, resistance heating may be used. This ensures that the heat pump is large enough to realize significant energy savings. For climates outside the Pacific Northwest with different heating season temperature profiles, it may make sense to use a different balance point.

Cold weather capable variable capacity equipment can be “oversized” for cooling loads while sized to meet all or most of the heating loads without the use of electric resistance heating. Variable capacity systems avoid the efficiency penalty associated with air conditioning oversizing because the system has excellent part load efficiency.

Aux heating –default control settings and inputs

Once the heat pump is sized adequately, the second prong in minimizing resistance heating is preventing it from running unnecessarily. The PTCS program requires resistance heating to be locked out above 35 ^{0}F “except when supplemental heating is required during a defrost cycle or when emergency heating is required during a refrigeration cycle failure” (BPA 2017). A lockout control such as this excludes resistance heat from operating during morning warmup or concurrently with the heat pump at unnecessarily warm outside conditions. The “gap” between the heat pump balance point of 30 ^{0}F and ER lockout at 35 ^{0}F is crucial to successful operation. If the heat pump is sized precisely to 30 ^{0}F, it will have little extra output capacity in the 30-35 ^{0}F range and therefore have difficulty increasing the house temperature on setback recovery. To generalize for specifications to be developed for other climates, it is therefore useful to place the ER lockout at least 5 ^{0}F above the balance point (Larson 2010).

Another important control not to overlook is the compressor lockout. Thermostats can be configured to turn the compressor off below a given outdoor temperature, however, to maximize energy savings, this should never be done. Rather, it is best to have no compressor lockout, or set it as low as possible, and allow the heat pump to run as much as it can. The heat pump will turn itself off when operating outside of design conditions or when the equipment undergoes a special cycle such as defrost.

Another technological solution to limiting resistance heat use when recovering from setback, regardless of heat pump size, is thermostat schedule anticipation. Often called “smart-start” or “optimum recovery,” this is a strategy which looks ahead at the temperature schedule. For example, if the setup is requested to be 68 ^{0}F at 6 AM, the thermostat may turn on just the heat pump at 3 AM to heat up from 64 ^{0}F. Such a strategy allows occupants to setback to a cooler night temperature, reduce energy use overnight, and not pay a resistance heat penalty on morning warmup. This feature is available on many modern thermostats although its implementation can vary widely.

Ideally updates to heat pump thermostatic control requirements will provide more clear criteria for showing compliance with the standards including:

- An approval process for heat pump thermostats based on their default control settings so that all market participants (building inspection, designers, contractors) will know what equipment is pre-approved without need for work arounds or enabling obscure settings
- Clear definitions of the minimum duration of pull up load that would trigger auxiliary heating without manual override. This should work for both scheduled setback or for occupants which treat thermostats like a light switch and regularly turn thermostats off during nighttime, work or while on vacation.

- Optimal start capability so the pull up load is extended long enough so that it can be met solely by heat pump operation without supplemental heat.
- Temperature threshold above which supplemental heating is locked out.
- Easy to evaluate acceptance test criteria that verify that heat pump equipment is adequately sized and that controls are installed and working according to their specification.

The 2021 amendments in the Washington State Energy Code contains a prohibition of electric resistance heating which touches on many of these criteria.[3]

Advanced crankcase heater controls or eliminate crankcase heaters

Technologies that can limit or eliminate the use of crankcase heaters include:

- Adjustable Thermostat Controls. Temperature sensor controls to limit operation of crankcase heater to when it is required due to outdoor temperatures and operation periods. This control can be installed after-market but may void compressor warranty. Alternatively, manufacturers can incorporate thermostatic controls into the system.
- Recycle Pump Down Control. Using a recycling pump down control which stores refrigerant away from the compressor during shutoff down or off periods. This technology includes a solenoid valve in the liquid line which closes when the set point temperature is reached. The compressor will continue to pump refrigerant from the low side to clear the line into the condenser. This prevents refrigerant being pulled into oil on the next cycle start up.

Heat pumps can avoid use of crankcase heater by taking advantage of compressors that are tolerant of refrigerant migration such as scroll compressors, controls for compressors speed or refrigerant to minimize or eliminate impact, or small heat exchanger tubing. It is also critical to go beyond the technological solutions to reduced crankcase operations, The inclusion of these technologies in a system and control mechanisms must be clearly identified in manufacturers literature and control mechanisms to enable informed product selection. Lastly, energy consumption associated with these ancillary components should be included in energy consumption data.

Conclusions

California and other states have embraced building heating electrification as a significant step towards total decarbonization of their economies. Efficient building space heating relies on the use of high efficiency heat pumps. As described above actual heat pump energy use is substantially higher than ideal simulated use. Broad use of improved thermostatic controls, improved heat pump designs are needed in the near term. This will take a coordinated effort by federal and state governments, utility incentive programs and equipment manufacturers to quickly commercialize and deploy fixes to the current shortcomings in heat pump operation. These results can be deployed more broadly if these fixes are incorporated as soon as possible into building energy codes, equipment test methods and appliance standards.

---

[3] **C403.1.4 Use of electric resistance and fossil fuel-fired HVAC heating equipment.** See exception 5 for heat pump controls to limit supplementary heating. https://sbcc.wa.gov/sites/default/files/2022-01/WSR_22_02_076_Full_WSEC_C_CR102.pdf

References

ACCA Manual J – 2016 *Residential Load Calculation.* Air Conditioning Contractors of America. Alexandria, VA

ACCA Manual S – 2014. *Residential Equipment Selection.* Air Conditioning Contractors of America. Alexandria, VA

Baylon, D., S. Strand, B. Davis, E. Kruse, and D. Robison. 2005. *Analysis of Heat Pump Installation Practices and Performance, Market Research Report*. Prepared for the Northwest Energy Efficiency Alliance. December 2005. http://www.nwalliance.org/research/reports/169.pdf

Bonneville Power Administration. 2017. *PTCS Air Source Heat Pump Installation Specification*. www.bpa.gov/-/media/Aep/energy-efficiency/residential/residential-ptcs-essentials/ashp-specifications.pdf

Bonneville Power Administration. 2019. *Air Source Heat Pump Commissioning, Controls & Sizing Baseline Field Study Report.* www.bpa.gov/-/media/Aep/energy-efficiency/momentum-savings/2019-bpa-heat-pump-field-study-final-report.pdf

Burke, A. 2019. *PTCS (Performance Tested Comfort Systems) Program Redesign Draft Recommendations*. November 21, 2019 www.bpa.gov/EE/NewsEvents/presentations/Documents/PTCS_Redesign_Brown_Bag_112119.pdf

CalISO 2022 *Supply trend: Energy in megawatts broken down by resource in 5-minute increments.* California Independent System Operator. https://www.caiso.com/todaysoutlook/pages/supply.aspx#section-supply-trend

CARB 2022. Website: *AB 32 Global Warming Solutions Act of 2006.* California Air resources Board. Accessed March 20, 2022 ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming-solutions-act-2006

CEC. 2020 California Energy Commission. Spreadsheet: *Long Run Marginal Emissions Factors CH4_Leak_20yr_15RA*. (20 year event horizon used for GWPs and emissions include methane leakage) File Creation date: 4/22/2020 https://efiling.energy.ca.gov/getdocument.aspx?tn=233260

CEC. 2022. *Final 2021 Integrated Energy Policy Report (IEPR) Volume I: Building Decarbonization.* February 2022. Publication No. CEC-100-2021-001-V1. www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2021-integrated-energy-policy-report

CLEE 2019. *California Climate Policy Fact Sheet: Renewables Portfolio Standard.* https://www.law.berkeley.edu/wp-content/uploads/2019/12/Fact-Sheet-RPS.pdf

Dryden, A., G. Pfotenhauer, N. Stone, S. Armstrong et al. 2021. *Getting to All-Electric Multifamily ZNE Construction. Draft Final Project Report.* EPC-15-097. March 2021. aea.us.org/wp-content/uploads/2021/11/Final_Report_15-097_Getting-to-All-Electric-Multifamily-Zero-Net-Energy-Construction_2021.10.22.pdf

E3 2020. *Time Dependent Valuation of Energy for Developing Building Efficiency Standards 2022 Time Dependent Valuation (TDV) and Source Energy Metric Data Sources and Inputs.* Energy and Environmental Economics, Inc. May 2020. https://efiling.energy.ca.gov/getdocument.aspx?tn=233345

Ecotope 2014. *Residential Building Stock Assessment: Metering Study*. Ecotope, Inc. Prepared for Northwest Energy Efficiency Alliance. https://neea.org/resources/2011-rbsa-metering-study

EIA 2022. *Natural Gas Consumption by End Use*. US Energy Information Administration. Release Date: 2/28/2022. https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

Emerson 2021. *Crankcase Heaters for Scroll Compressors*. Emerson/Copeland Application Engineering Europe. Ref: TI_Scroll_Heater_E_Rev00. Date of last update: Apr-21. https://climate.emerson.com/documents/crankcase-heaters-for-scroll-compressors-technical-information-en-gb-7486018.pdf

IPCC 2018. *Summary for Policymakers. In: Global Warming of 1.5°C.* An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways... World Meteorological Organization, Geneva, Switzerland. //www.ipcc.ch/sr15/chapter/spm/

Larson, B., B. Davis, and D. Baylon. 2010. *Modeled Heat Pump Retrofit Predictions with 'Right' Sizing and Outdoor Temperature Lockout Controls. Revised August 27, 2010*. ecotope-publications-database.ecotope.com/2010_006_ModeledHeatPumpRetrofit.pdf

NREL 2013. Energy Analysis: Biogas Potential in the United States. National Renewable Energy Laboratory. NREL/FS-6A20-60178 • October 2013 https://www.nrel.gov/docs/fy14osti/60178.pdf

SB 1383, 2016. (Lara). *Short-lived climate pollutants: methane emissions: dairy and livestock: organic waste: landfills.* leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB1383

Sudarshan, A. 2013. *Deconstructing the `Rosenfeld Curve: Making sense of California's low electricity intensity*. Energy Economics Volume 39, September 2013, Pages 197-207.

Wilcox, B., A. Conant, and R. Chitwood. 2018. *PGE Central Valley Research Homes, Variable Capacity Heat Pumps, Evaluation of Ducted and Ductless Configurations 2016-2017.* Pages 59-60.

Wilcox, B., A. Conant, and R. Chitwood. 2019. *Central Valley Research Homes, Variable Capacity Heat Pumps, Evaluation of Sizing and Control Settings 2017-2018.* Pages 65-67.