Analysis of NOx Emissions from Hybrid Heating Technologies in California

Nelson Dichter

University of California, Davis
Western Cooling Efficiency Center

UC DAVIS
Western Cooling Efficiency Center

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Contacts

Nelson Dichter, Western Cooling Efficiency Center, ncdichter@ucdavis.edu.

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Executive Summary

A hybrid heating system consists of a reduced-capacity electric heat pump paired with a natural gas furnace for auxiliary heat. These systems are an alternative to all-electric heat pumps and traditional gas furnaces paired with air conditioners. A hybrid heating system uses the electric heat pump as the primary source of heat and switches to the gas furnace for auxiliary heat when necessary based on a programmed control strategy.

Nitrogen oxides (NOx), harmful and toxic greenhouse gases, are released when gas is burned at high heat in a furnace. Whole-building annual energy simulations were conducted using EnergyPLus to estimate NOx annual emissions from low NOx furnaces (40 ng/J), ultra-low NOx (14 ng/J) furnaces and hybrid heating systems (a heat pump with a low NOx furnace for auxiliary heat) in single-family residential buildings in California. Carbon dioxide (CO2) emissions were also estimated for these systems. When the results were averaged across California, weighted by the population in each California climate zone, the hybrid heating system reduced NOx emissions by 95%-100% and CO2 emissions by 67%-69% compared to a low NOx furnace. Ultra-low NOx furnaces reduce NOx emissions by 65% but do not reduce CO2 emissions compared to a low NOx furnace. This study shows hybrid heating systems are a viable alternative to reduce NOx and CO2 emissions.

Introduction

Nitrogen oxides (NOx) are a group of pollutants that form smog through reactions with sunlight and other chemicals in the atmosphere and contribute to acid rain, global warming, and respiratory issues like asthma. NOx is produced from a reaction between atmospheric nitrogen and oxygen during the combustion of fossil fuels, such as the combustion of natural gas in furnaces to heat buildings.

Most residential buildings in California are heated and cooled by either a natural gas furnace paired with an air conditioner or an electric heat pump. Since heat pumps operate on electricity, they do not have direct emissions from burning natural gas. Historically, natural gas furnaces have been less expensive to both purchase and operate; however, increasing regulations in emissions standards are increasing the cost of natural gas furnaces, shrinking the gap between the system cost of heat pumps and natural gas furnaces paired with an air conditioner.

A standalone heat pump must be sized for either the heating load or the cooling load of the building, whichever is larger. Since most buildings do not have balanced heating and cooling loads, sizing a standalone heat pump results in oversizing the capacity in one mode or the other. In residential buildings in many climate zones, the heating load is significantly larger than the cooling load. In these climates, the cost of a heat pump is more than a traditional furnace paired with an air conditioner, sized for the smaller cooling load, because the heat pump must be sized for the larger heating load.

Hybrid heating systems, which contain a heat pump paired with a low NOx gas furnace, are an alternative technology that would reduce annual NOx emissions compared to low and ultra-low NOx furnaces paired with an air conditioner. In a hybrid system, the heat pump is used as the primary source of heat and the furnace serves as the auxiliary source of heat. The heat pump operates during mild temperatures, as the outdoor air temperature drops and the heat pump can no longer meet the heating load of the building, the system turns off the heat pump and switches to the natural gas furnace. By reducing the number of hours in the year that the furnace must operate, the hybrid heating system reduces the annual NOx emissions of the furnace. Since the furnace can be sized to meet the heating load of the building during the coldest hours of the year, the heat pump can be sized based on the cooling load instead of the heating load, resulting in reduced system cost.

Methodology

Whole-building annual energy simulations were conducted using EnergyPlus to estimate the annual NOx emissions from low NOx furnaces (40 ng/J), ultra-low NOx (14 ng/J) furnaces, and hybrid heating systems (a heat pump with a low NOx furnace for auxiliary heat) in California residential buildings. The modeled hybrid heating system used an electric heat pump as the primary source of heat and a low NOx furnace as the auxiliary source of heat. The annual NOx and CO_2 emissions of each heating system were simulated in each of California's 16 climate zones.

Climate

Weather was simulated in each climate zone using typical meteorological year weather data. The population distribution reported in the 2010 California census was divided among the California climate zones shown in Figure 1 [1]. The resulting population distribution among the California climate zones is shown in Table 1.

CLIMATE ZONE	POPULATION	%
1	184447	0%
2	933547	3%
3	3819705	10%
4	2004051	5%
5	395476	1%
6	2806994	8%
7	2125136	6%
8	4605438	12%
9	5873325	16%
10	4008503	11%
11	1059718	3%
12	4709701	13%
13	2364450	6%
14	910003	2%
15	669960	2%
16	554592	1%

Table 1 – Population distribution among California climate zones

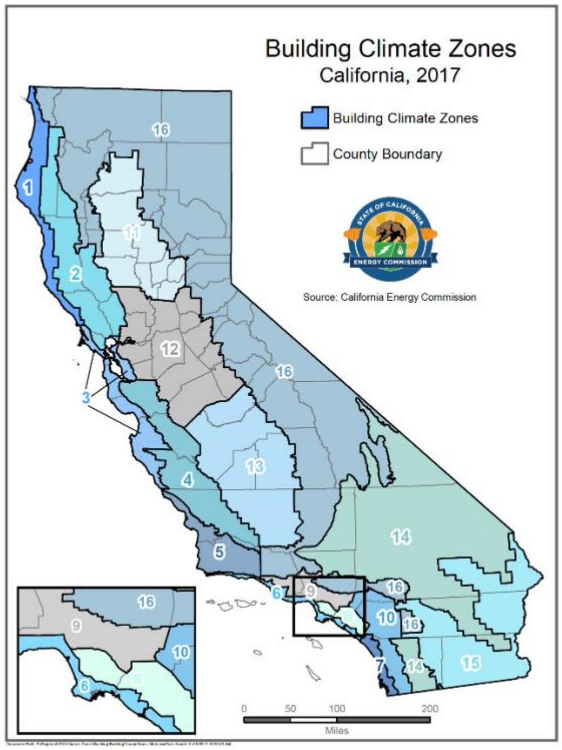

Figure 1 – California Climate Zones

Geometry

The baseline building that was modeled in EnergyPlus was a single-family building with 2,400 ft^2 of conditioned spa ce and 1,200 ft^2 of unconditioned attic space. The geometry of the building was based on an EnergyPlus example file for a single-family residential building. A rendering of the single-family building is shown in Figure 2. The model does not represent a particular single-family building nor does it attempt to represent an average of all single-family buildings. Instead, it was designed to be an example of a "typical" single-family building. Two levels of insulation were simulated, one that is representative of new construction (R-13 in the walls and R-19 in the ceiling) and one that is representative of existing construction (R-8 in the walls and R-11 in the ceiling).

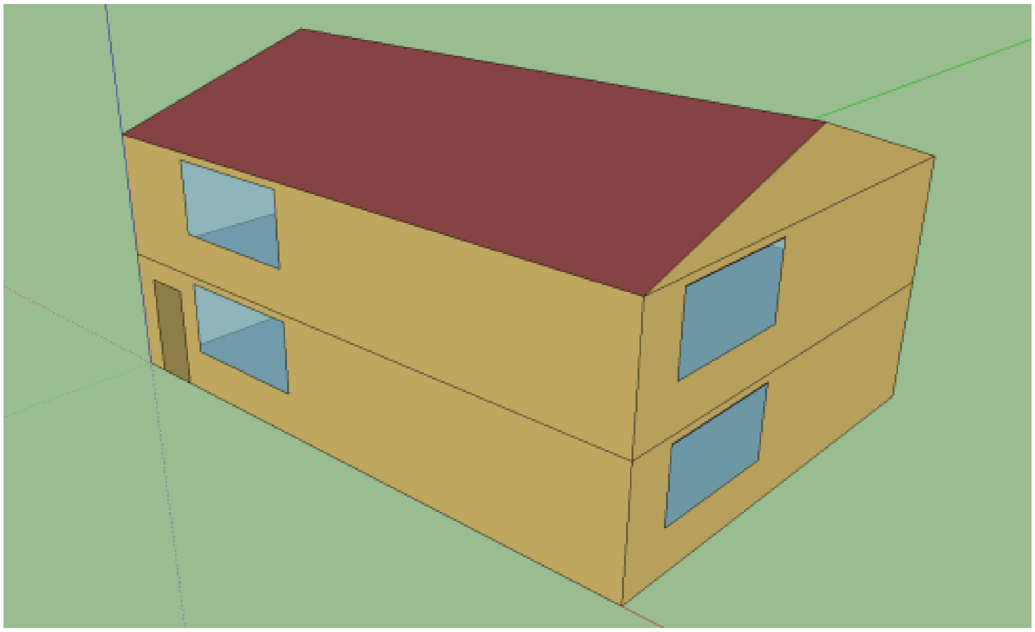

Figure 2 - Rendering of the single-family building modeled in EnergyPlus

HVAC Systems

The baseline single family building was modeled with a single speed air conditioner and a low NOx furnace. The air conditioner had a Seasonal Energy Efficiency Ratio (SEER) of 14 and the low NOx furnace had an efficiency of 80%. The hybrid heating system was modeled as a single-speed heat pump and a low NOx furnace. The heat pump had a SEER of 14 and a seasonal performance factor (HSPF) of 8.2. the low NOx furnace had an efficiency of 80%. Generic performance curves were used to model each Heating Ventilation and Air Conditioning (HVAC) system.

The air conditioner and the heat pump were sized based on the cooling load of the building. Three sizing factors (the ratio between the rated cooling capacity and the design day load) were used to size the equipment: 1, 1.3 and 1.7. A sizing factor of 1 represents a worst case-scenario, meaning that the system is barely able to meet the cooling load at the design day conditions. It is common practice to size systems with a sizing factor between 1.33 and 1.48 to ensure that the load can be met all year [2]. The heating setpoint was set to 68 °F and the cooling setpoint was set at 74 °F. The hybrid heating system was controlled using two different strategies: the indoor air-control strategy and the outdoor-air control strategy.

Indoor-Air Strategy: The electric heat pump is used to meet the heating load of the building unless its capacity is inadequate and the indoor air temperature drops more than 1 °F below the setpoint temperature, at which point the heating load of the building is met using the low NOx furnace. The indoor-air control strategy simulates the behavior of a thermostat installed alongside hybrid heating systems.

Outdoor-Air Strategy: The electric heat pump is used to meet the heating load of the building unless the indoor air temperature drops more than 1 °F below the setpoint temperature or the outdoor air temperature drops below the switchover temperature, at which point the heating load of the building will be met using the low NOx furnace. The Outdoor-air control strategy simulates the behavior of a thermostat with an outdoor air temperature sensor.

Controlling the heat pump based on the indoor-air temperature minimizes natural gas use and direct NOx emissions while maintaining occupant comfort by using the electric heat pump whenever its capacity is adequate to maintain the heating setpoint. Controlling the heat pump using the outdoor-air temperature reduces operating costs by preventing the heat pump from operating at low outdoor temperatures when its efficiency is lowest. The indoor-air control strategy is the default setting for many hybrid heating systems.

NOx Emissions

The NOx emissions were calculated based on the heat, in Joules, delivered by the furnace to the space. For low NOx furnaces an emission rate of 40 ng/J was assumed and for ultra-low NOx furnaces an emission rate of 14 ng/J was assumed. All other performance parameters of the low NOx and ultra-low NOx furnaces were assumed to be identical. Thus, the ultra-low NOx furnace resulted in a 65% reduction in annual NOx emissions.

CO_2 Emissions

The CO_2 emissions of each simulated case were calculated based on the annual natural gas and electricity used to heat the building. According to the US Energy Information Administration [2], 117 pounds of CO_2 are emitted into the atmosphere for every million BTUs of natural gas burnt. Historical data on electricity production and the consequential CO_2 emissions was used to convert the electricity used to heat the building to emissions. According to the EIA, 113 pounds of CO_2 were emitted into the atmosphere for every million BTUs of electricity produced in California in 2016.

Results

Control Strategies

Figure 3 shows the operation of the heat pump and furnace in the hybrid heating system using the outdoor-air control strategy from January 31st to February 1st in California climate zone 16. The building was insulated to represent new construction (R-13 in the walls and R-19 in the ceiling) and the sizing factor for the heat pump was 1.7. For these examples, a cold climate zone and a large sizing factor was selected to demonstrate the difference in the behavior of the two control strategies; in warmer climate zones and with smaller sizing factors the behavior of the two control strategies is less distinct. Whenever the outdoor air temperature dropped below 32 °F, the heat pump was turned off and the system switched to furnace operation.

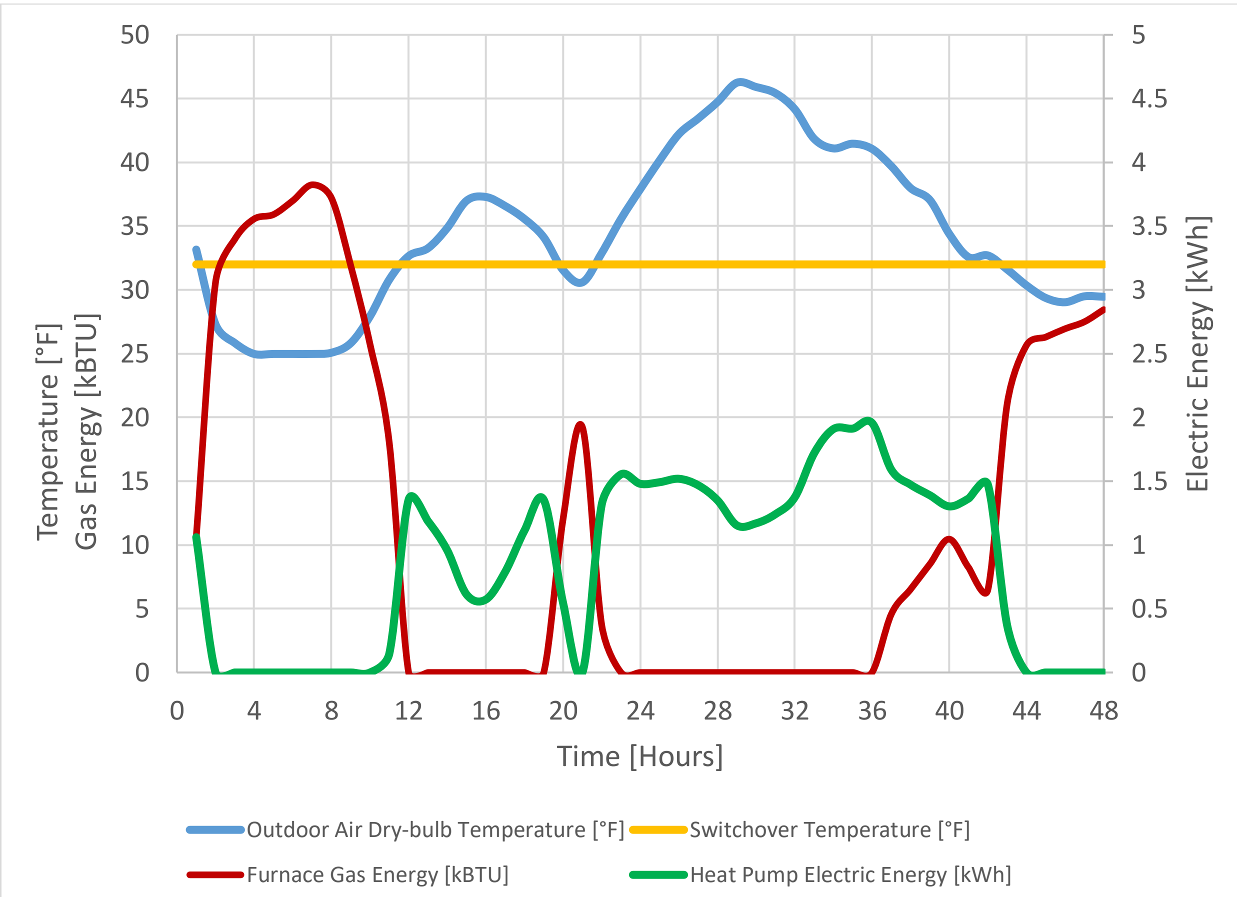

Figure 3 – Hybrid heating system operating profile using the outdoor-air control strategy from January 31st to February 1st in California climate zone 16.

Figure 4 shows the operation of the heat pump and furnace in the hybrid heating system using the indoor-air control strategy from January 31st to February 1st in California climate zone 16. The building was insulated to represent new construction (R-13 in the walls and R-19 in the ceiling) and the sizing factor for the heat pump was 1.7.

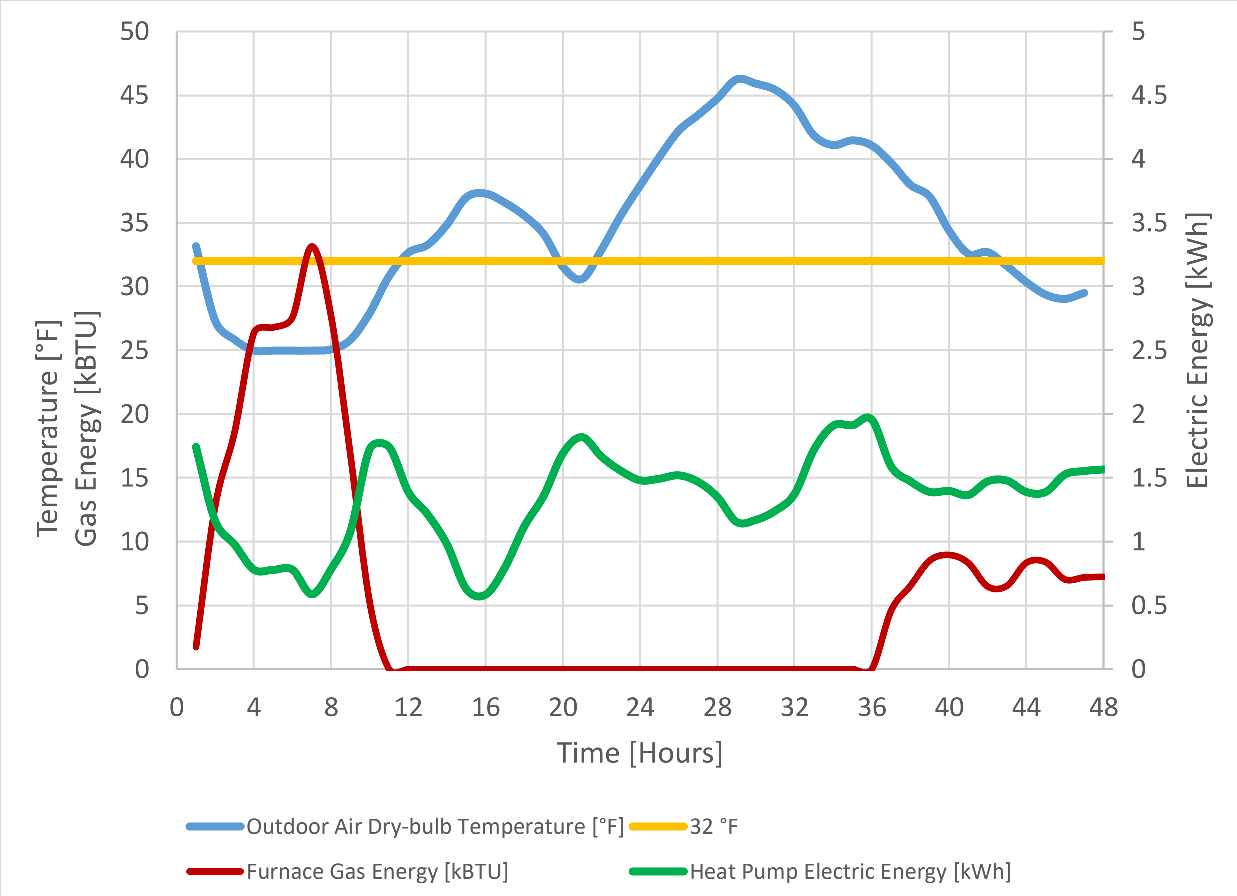

Figure 4 - Hybrid heating system operating profile using the indoor-air control strategy from January 13st to February 1st in California climate zone 16.

Using the indoor-air control strategy, the hybrid heating system relied more heavily on the heat pump and only switched to furnace operation when the system was unable to satisfy the heating load of the building.

Annual NOx emissions

Based on the simulation results, the annual NOx emissions of the hybrid heating system were compared to that of the baseline low NOx furnace. Figure 5 shows the annual NOx emissions reduction of a hybrid heating system compared to a low NOx furnace with two insulation levels and both indoor-air and outdoor-air control strategies (CS). In cases using the outdoor-air control strategy, the switchover temperature was set to 32 °F. The heat pump in the hybrid heating system was sized based on the cooling load with a typical sizing factor of 1.3 using design day calculations. Annual NOx emissions reductions that would be achieved with an ultra-low NOx furnace (65%) are indicated by the black line.

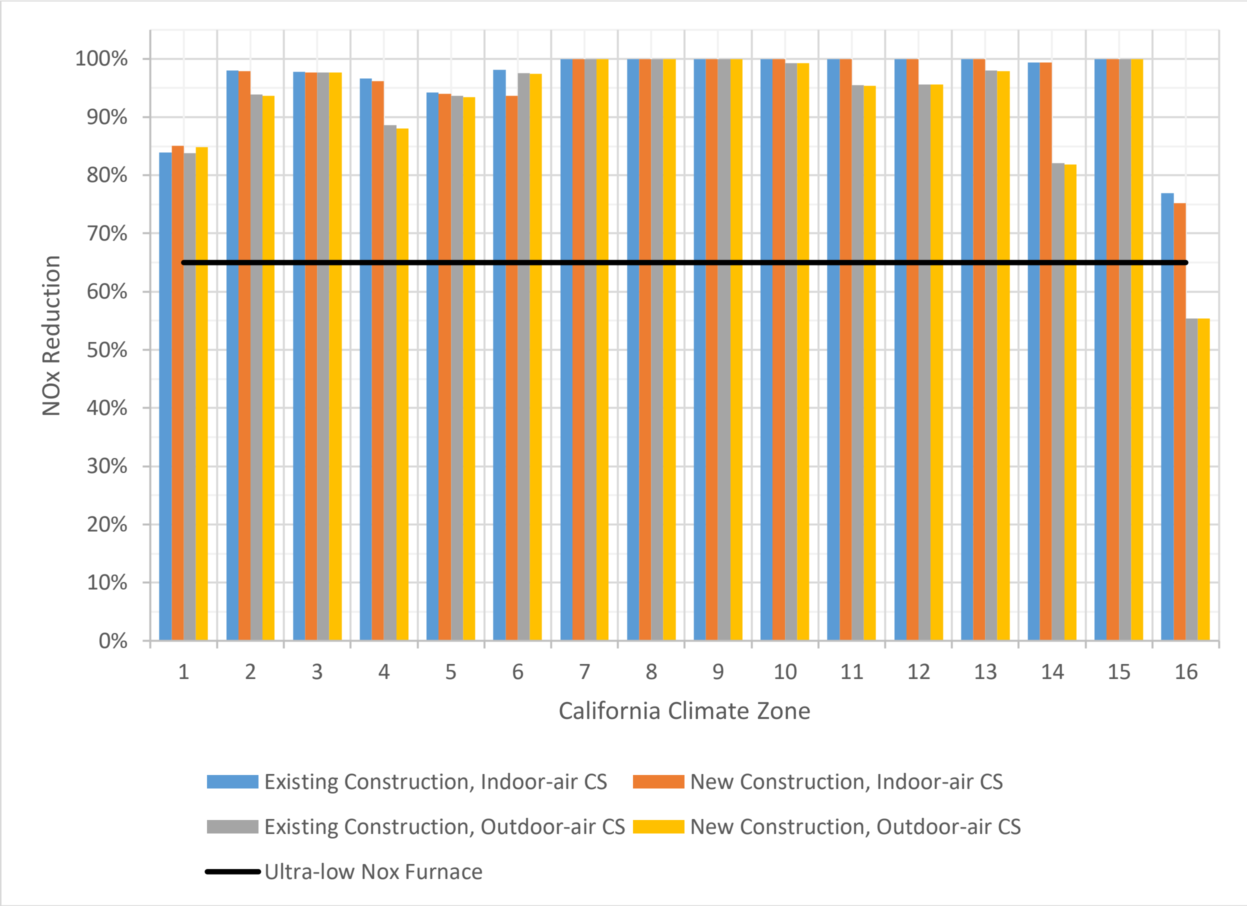

Figure 5 – Annual NOx emissions reduction of a hybrid heating system compared to a low NOx furnace. The heat pump in the hybrid heating system was sized based on the cooling load with a typical sizing factor of 1.3.

Using the indoor-air control strategy, the hybrid heating system was able to reduce annual NOx emissions by more than an ultra-low NOx furnace in all California climate zones. Using the outdoor-air control strategy, the hybrid heating system was able to reduce annual NOx emissions by more than an ultra-low NOx furnace in all California climate zones except for California climate zone 16. In most cases, the hybrid heating systems using the indoor-air control strategy had similar or greater NOx emission reductions than the hybrid heating systems using the outdoor-air control strategy. The better insulated building had a smaller thermal load, resulting in fewer annual heater operating hours and NOx emissions. However, the building insulation had little effect on the percentage of the NOx emissions reduction when comparing the hybrid heating system to the low NOx furnace.

Figure 6 shows the annual NOx emissions reduction of a hybrid heating system compared to a low NOx furnace with both indoor-air and outdoor-air control strategies and multiple sizing factors. In these cases, the building was insulated to represent new construction (R-13 in the walls and R-19 in the ceiling). In cases using the outdoor-air control strategy, the switchover temperature was set to 32 °F.

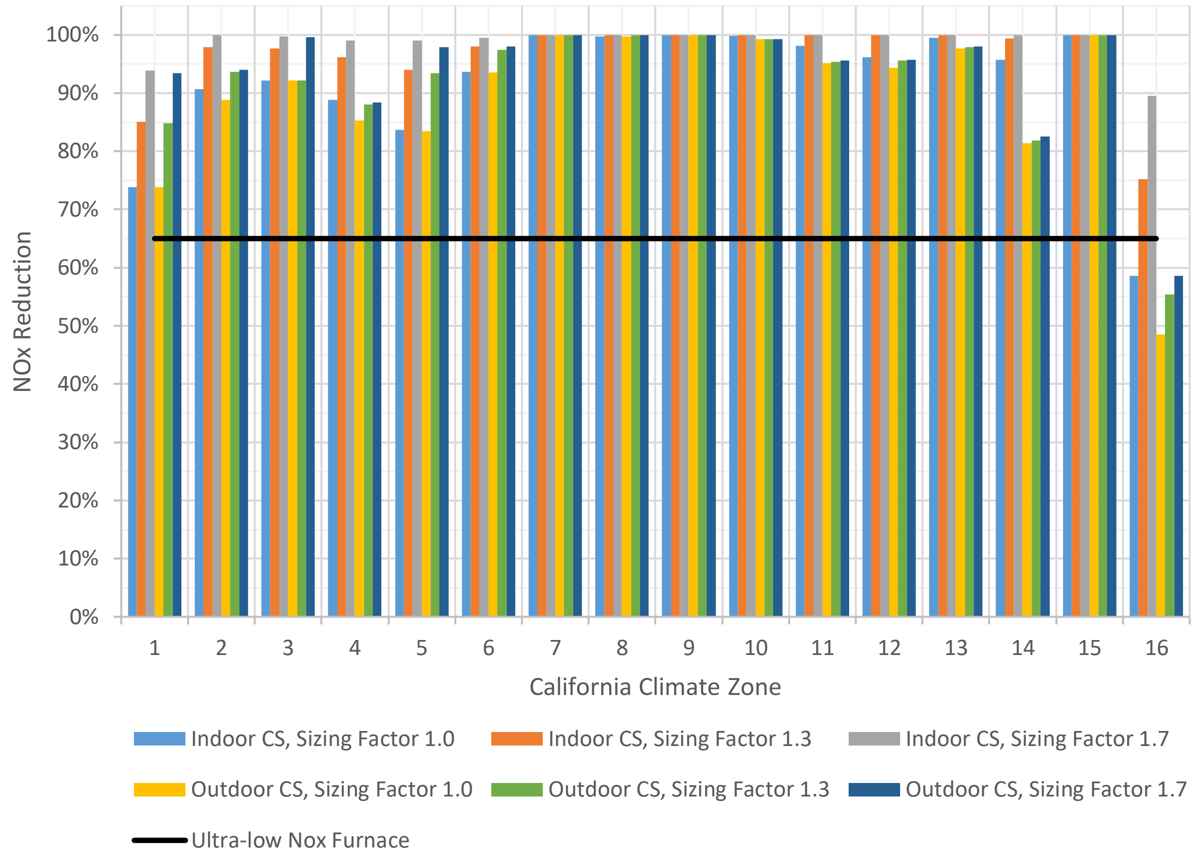

Figure 6 - Annual NOx emissions reduction of a hybrid heating system compared to a low NOx furnace. The heat pump in the hybrid heating system was sized based on the cooling load with three different sizing factors.

As the sizing factor increased, the annual NOx emission reductions also increased. With a larger heat pump, the hybrid heating system satisfied more of the heating load with the heat pump instead of the furnace, resulting in less natural gas use and consequently reduced annual NOx emissions. When the sizing factor was 1.3 or greater, the hybrid heating system using the indoor-air control strategy was able to achieve larger NOx reductions than an ultra-low NOx furnace in all California climate zones. However, due to the cold winters in California climate zone 16, the hybrid heating system operated at ambient temperatures lower than the switchover temperature (32 °F) approximately 36% of the time. As a result, in this climate zone the outdoor-air control strategy achieves significantly less NOx emission reductions than the indoor-air control strategy regardless of the heat pump sizing factor.

Annual CO_2 emissions

An additional benefit of hybrid heating systems is a reduction in CO_2 emissions. Although ultra-low NOx furnaces reduce NOx emissions when compared to a low NOx furnace, they still burn the same amount of natural gas to provide a given amount of heat. Since CO_2 emissions are a direct consequence of burning natural gas, ultra-low NOx furnaces emit the same amount of CO_2 as the low NOx furnaces that they replace. Although CO_2 emissions are also embedded in the electricity that powers electric heat pumps, hybrid heating systems can significantly reduce CO_2 emissions when compared to natural gas furnaces due to the large amount of renewables (which, if current trends continue, will increase in the future) on the California grid and the efficiency of the electric heat pump.

Figure 7 shows the annual CO_2 emissions reduction of a hybrid heating system compared to a low NOx furnace with both indoor-air and outdoor-air control strategies and multiple sizing factors. The building was insulated to represent new construction (R-13 in the walls and R-19 in the ceiling). In cases using the outdoor-air control strategy, the switchover temperature was set to 32 °F.

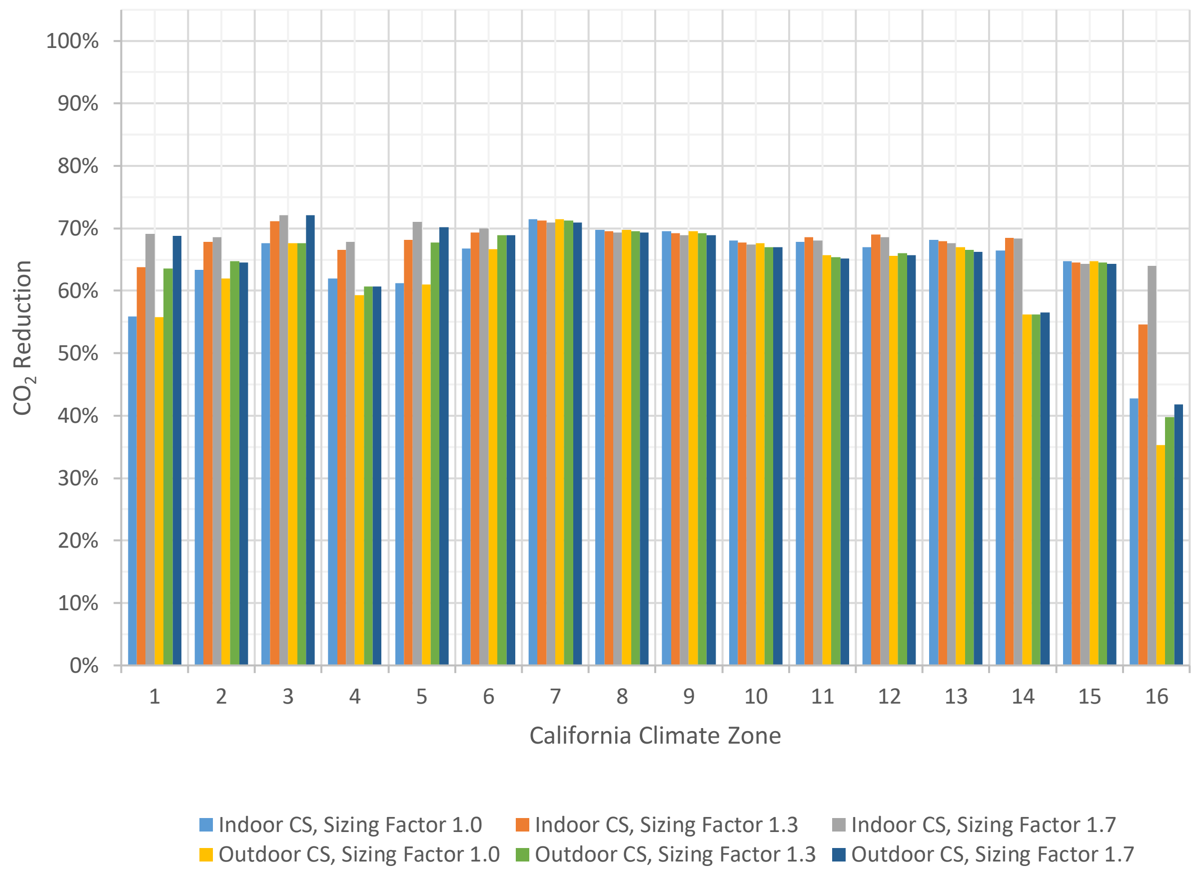

Figure 7 - Annual CO_2 emissions reduction of a hybrid heating system compared to a natural gas furnace.

When compared to a natural gas furnace, the hybrid heating system achieved CO_2 emissions reductions between 35% and 72%. In the colder climates of climate zone 14 and 16, the control strategy had a significant impact on the CO_2 emissions reductions, with the indoor-air control strategy achieving higher CO_2 emissions reductions than the outdoor-air control strategy. As the sizing factor increased, the annual CO_2 emission reductions increased in climate zones 1 through 6 and 16 and stayed approximately the same in climate zones 7 through 15.

Summary

The population distribution in California was used to weight the simulation results. The population-weighted California average annual NOx and CO_2 emissions reduction of a hybrid heating system compared to a low NOx furnace are shown in Table 2.

Control Strategy	Sizing Factor	NOx Reduction	CO_2 Reduction
Indoor-air	1	96%	67%
	1.3	99%	69%
	1.7	100%	69%
Outdoor-air	1	95%	66%
	1.3	97%	67%
	1.7	97%	67%

Table 2 – Population-weighted annual NOx and CO_2 emissions reduction of a hybrid heating system compared to a low NOx furnace.

In California, the hybrid heating system, when compared to a low NOx furnace, resulted in an annual NOx emissions reduction of more than 95% on average for all control strategies and sizing factors simulated. The average CO_2 emissions reduction of the hybrid heating system, when compared to a low NOx furnace, was between 67% and 69%.

Conclusion

Hybrid heating systems reduced NOx emissions in residential buildings by as much as 90% in the coldest climates and nearly 100% in milder climates compared to a low NOx furnace. This reduction is more than the 65% annual NOx reduction from ultra-low NOx furnaces. An additional benefit of hybrid heating systems is a reduction in CO_2 emissions, which ultra-low NOx furnaces cannot achieve. When compared to a low NOx furnace, hybrid heating systems reduced NOx emissions by more than 96% and CO2 emissions by between 67% and 69% on average in California. Based on these results, regulations aimed at reducing NOx emissions in residential buildings in California should include a provision for hybrid heating systems.

References

[1] "California Energy Maps," California Energy Commission, 2019. [Online]. Available: https://ww2.energy.ca.gov/maps/renewable/building_climate_zones.html.

[2] Office of Energy Efficiency & Renewable Energy, "Residential HVAC Installation Practices: A Review of Research Findings," U.S. Department of Energy, 2018.

[3] "Energy-Related Carbon Dioxide Emissions by State," U.S. Energy Information Administration, November 2019. [Online]. Available: https://www.eia.gov/environment/emissions/state/analysis/.

[4] "Electric Power Monthly," U.S. Energy Information Administration, November 2019. [Online]. Available: https://www.eia.gov/electricity/monthly/.

[5] "Natural Gas Prices," U.S. Energy Information Administration, November 2019. [Online]. Available: https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_m.htm.