Analysis of Greenhouse Gas Emissions from Residential Heating Technologies in the USA

By: Nelson Dichter and Aref Aboud

UC DAVIS
Western Cooling Efficiency Center

WCEC Technical Report

September 15, 2020

Recommended Citation

Dichter, N., & Aboud, A. (2020). ***Analysis of Greenhouse Gas Emissions from Residential Heating Technologies in the USA.*** UC Davis Western Cooling Efficiency Center. https://wcec.ucdavis.edu/wp-content/uploads/GHG-Emissions-from-Residential-Heating-Technologies-091520.pdf

Acknowledgement

The researcher acknowledges Trane Technologies for funding this research.

Contacts

Theresa Pistochini, UC Davis Western Cooling Efficiency Center, tepistochini@ucdavis.edu

EXECUTIVE SUMMARY

Whole-building annual energy simulations were conducted using EnergyPlus to estimate the change in annual CO_2 emissions that would result from the replacement of natural gas furnaces with heat pumps in residential buildings across the contiguous 48 states in the United States of America. Four different heat pumps were simulated; a single-speed all electric heat pump, a variable-speed all electric heat pump, a single-speed dual-fuel heat pump, a variable-speed dual-fuel heat pump. Historical weather and marginal emissions rates from 2019 were simulated for over 200 locations across the USA. Each location simulated represents a unique combination of DOE climate zone and electric utility territory.

When compared to a natural gas furnace, the simulated heat pumps reduced CO_2 emissions in 15 states. The single-speed all electric heat pump reduced CO_2 emissions in 4 states, the variable-speed all electric heat pump reduced CO_2 emissions in 8 states, the single-speed dual-fuel heat pump reduced CO_2 emissions in 9 states, and the variable-speed dual-fuel heat pump reduced CO_2 emissions in 15 states. The simulated heat pumps reduced CO_2 emissions by more than 10% in nine states and by more than 30% in 3 states. In the other 33 states, the simulated heat pumps increased CO_2 emissions when compared to a natural gas furnace by as much as 155%.

The single-speed dual-fuel heat pump emitted less CO_2 annually than the variable-speed electric heat pump in the 17 states where more than 15% of the electric power was generated through the combustion of coal except for 1 state where they were approximately equal. In the 31 states where less than 15% of the electric power was generated through the combustion of coal, the variable-speed electric heat pump emitted less CO_2 annually than the single-speed dual-fuel heat pump in 9 states, the single-speed dual-fuel heat pump emitted less CO_2 annually than the variable-speed electric heat pump in 20 states, and emissions from the two heat pumps were approximately equal in 2 states.

If electric grids across the USA completely decarbonize in the future, between 65% and 90% of the CO2 emissions reductions that would be achieved by all-electric heat pumps operating on a decarbonized grid would still be realized by dual-fuel heat pumps that are in service after that grid transformation.

INTRODUCTION

Greenhouse gases (GHGs) are a group of compounds that have a high transmittance of most electromagnetic wavelengths of solar radiation but low transmittance of infrared (heat) radiation. The earth is continuously heated by solar radiation from the sun and cooled by emitting infrared radiation to the sky. When higher levels of GHGs are present in the atmosphere, more of the radiation being emitted by the earth is reflected back on its surface rather than escaping into space while solar radiation is still able to penetrate the atmosphere. By trapping energy within earth's atmosphere, GHGs contribute to global climate change. GHGs include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), and chlorofluorocarbons (CFC). Carbon dioxide is emitted as a byproduct of the combustion of fossil fuels (coal, natural gas, petroleum). The majority of GHG emissions from human activities are in the form of CO_2; 81% of the net global GHG emissions in 2018 were CO_2 [1].

Many regulatory agencies are pursuing electrification (converting natural gas appliances to electric appliances in new and existing construction) as a means of reducing carbon dioxide emissions that result from natural gas combustion. Although electric appliances do not emit greenhouse gasses directly, there are emissions embedded in the electricity that powers them. The embedded emissions depend on the makeup and operation of the portfolio of power generation facilities of a particular electric grid.

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. Historically, natural gas furnaces have been less expensive to both purchase and operate; however, more aggressive standards limiting emissions from natural gas appliances 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. Electric heat pumps do not directly emit GHGs, but instead incur indirect emissions which depend on the emissions produced by the electricity generation and distribution infrastructure from which they are powered.

Electric grids are comprised of four main components: the generators which produce the electricity, the transmission lines that carry the high voltage electricity over long distances, the distribution network which transmits the electricity from the transmission lines to homes and buildings, and the load which draws power from the electric grid. The generators are the main component responsible for GHG emissions; however, the efficiency of the energy distribution infrastructure also plays a role in emission rates. On one end of the spectrum, if the electricity powering heat pumps is produced by renewable sources (solar, wind, hydroelectric, etc.) the indirect GHG emissions rate is zero. The indirect GHG emissions rate of electric heat pumps powered by modern natural gas burning power plants are similar to the direct emissions rates of natural gas furnaces. On the other end of the spectrum, if coal fired power plants are used to generate electricity to power heat pumps, the indirect GHG emissions rate is two to three times higher than the direct emissions rates of natural gas furnaces. Most electric grids have a diverse portfolio of power generation assets including some mixture of renewables, natural gas, and coal. The deployment of these assets varies depending on availability and demand.

Dual-fuel heating systems, which contain an electric heat pump paired with a gas furnace, are an alternative technology that, depending on the makeup of the electric grid, could reduce annual GHG emissions in some regions compared to furnaces paired with an air conditioner and all-electric heat pumps. In a dual-fuel system, the electric 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 operates, the dual-fuel heating system reduces the annual GHG emissions of the furnace. Conversely, by operating the furnace during the coldest hours of the year, the dual-fuel heating system avoids using electric resistance auxiliary heat or operating the heat pump when it is least efficient, both of which incur high GHG emission rates.

The average carbon intensity (tons of CO_2 emissions per GWh of electricity generation) of electric grids varies across the USA from 133 tons/GWh in Washington to 298 tons/GWh in West Virginia with a United States average of 202 tons/GWh [2]. However, when considering the GHG emissions from increasing the load on an electric grid (such as through widespread adoption of electrification) it is important to consider the marginal emissions rate (MER).

Utility grid operators respond to fluctuations in load on the electric grid by increasing or decreasing the amount of power that is purchased from various generation sources. These generation sources that operate on the margin are usually the most expensive and highest emitting power generators in the portfolio and contribute to the MER. As a result, the MER is almost always higher than the average carbon intensity of an electric grid. For example, although the state of Washington has one of the cleanest power generation portfolios in the USA, it has many coal powerplants that operate on its margin contributing to an average MER of approximately 2,026 tons/GWh.

Currently, electric power production in the United States relies heavily on non-renewable sources such as coal and natural gas. A breakdown of the energy sources for electricity generation in the U.S.A. is shown in Figure 1. However, because of increased investment in renewable energy infrastructure and technology research, renewable energy is expected to see a large increase in the coming years. The increase in renewable energy power production coincides with a decrease in investment and reliance on coal fueled power production. Natural gas burning power generation is expected to remain relatively constant in the coming years with nuclear generation expecting to see a slight decrease [3]. This shift in power production follows the trend of the increasing number of municipalities pledging to drastically decrease their emissions in order to combat climate change.

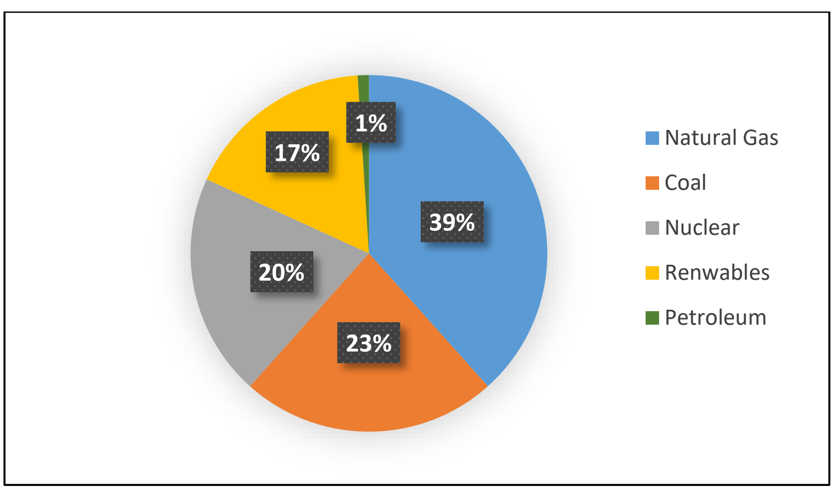


Figure 1 – Percent Contribution of Different Sources to United States Energy Production

METHODOLOGY

Whole-building annual energy simulations were conducted using EnergyPlus to estimate the annual CO_2 emissions from different heating systems in residential buildings across the contiguous 48 states in the United States of America (USA). Location variations in weather were accounted for as well as variations in indirect GHG emissions based on the MER of the local electric grid.

Climate

Energy use for heating and cooling a building is highly dependent on ambient meteorological conditions. According to the International Energy Conservation Code (IECC), the continental United States can be categorized by seven different climate zones. The climate zones range from hot and humid to very cold. The different climate zones and the descriptors they fall under can be found in Table 1. A map of the USA overlaid with the climate zones is shown in Figure 1 [4].

Descriptor	Climate Zones
Hot-Humid	1,2,3
Mixed-Humid	3,4
Hot-Dry	2,3
Mixed-Dry	4
Cold	5,6
Very-Cold	7

Table 1 – United States Climate Zones

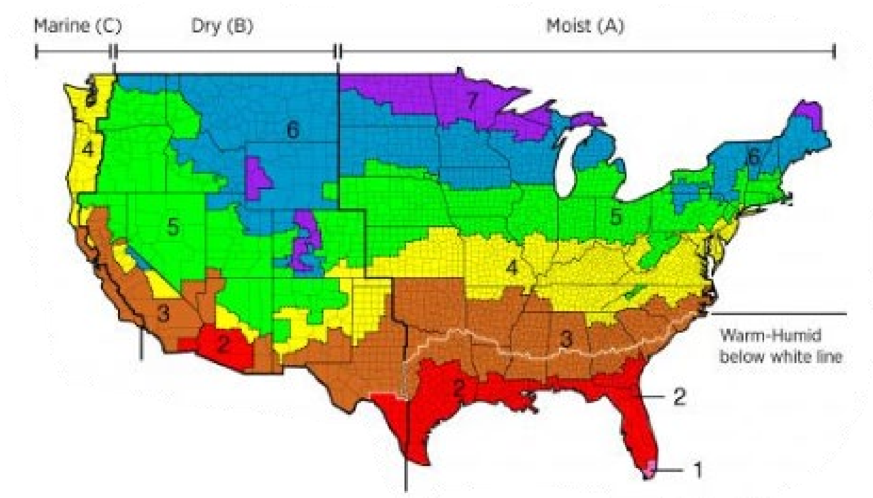
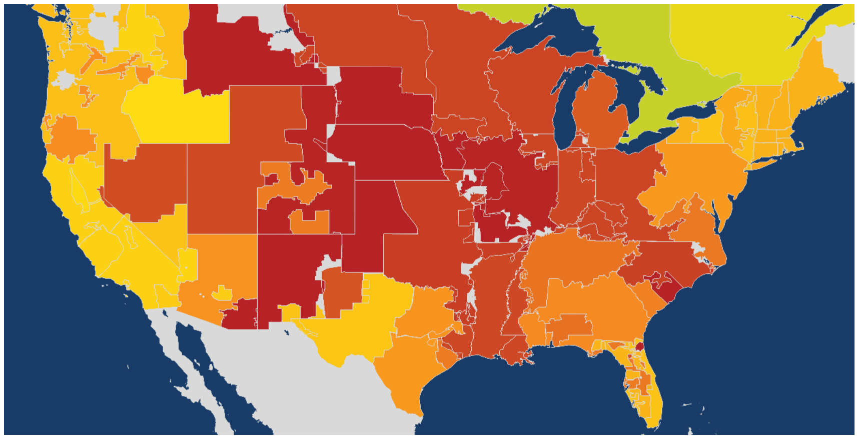


Figure 2 – United States Climate Zones

Electricity Generation

The USA is divided into many electric grid territories shown in Figure 2 [5]. Electric grid territories are not contained by state lines; some cover only a part of a state while others cover regions in multiple states.



Source: https://www.watttime.org/explorer/ - 4/42.99/-98.38/-0.4/1

Figure 3 - Map of Energy Grids in the USA

Utility operators manage a diverse portfolio of generation sources that varies from state to state and between grid territories. These generation sources usually include some combination of nuclear, coal, natural gas, solar, hydro, wind, geothermal, biomass and biogas. Additionally, electricity can be imported from out of state or generation can be shifted from peak to off-peak hours using energy storage. These generation facilities differ from each other in cost, responsiveness, availability, reliability, and emissions. As such, some are better suited for serving a constant baseload, while some excel at responding to rapid fluctuations in a dynamic load profile and others minimize the environmental impact of electricity generation.

For example, the generation sources that were used to meet the electric demand of California utility customers throughout the day on August 16, 2019 are shown in Figure 3 [6].

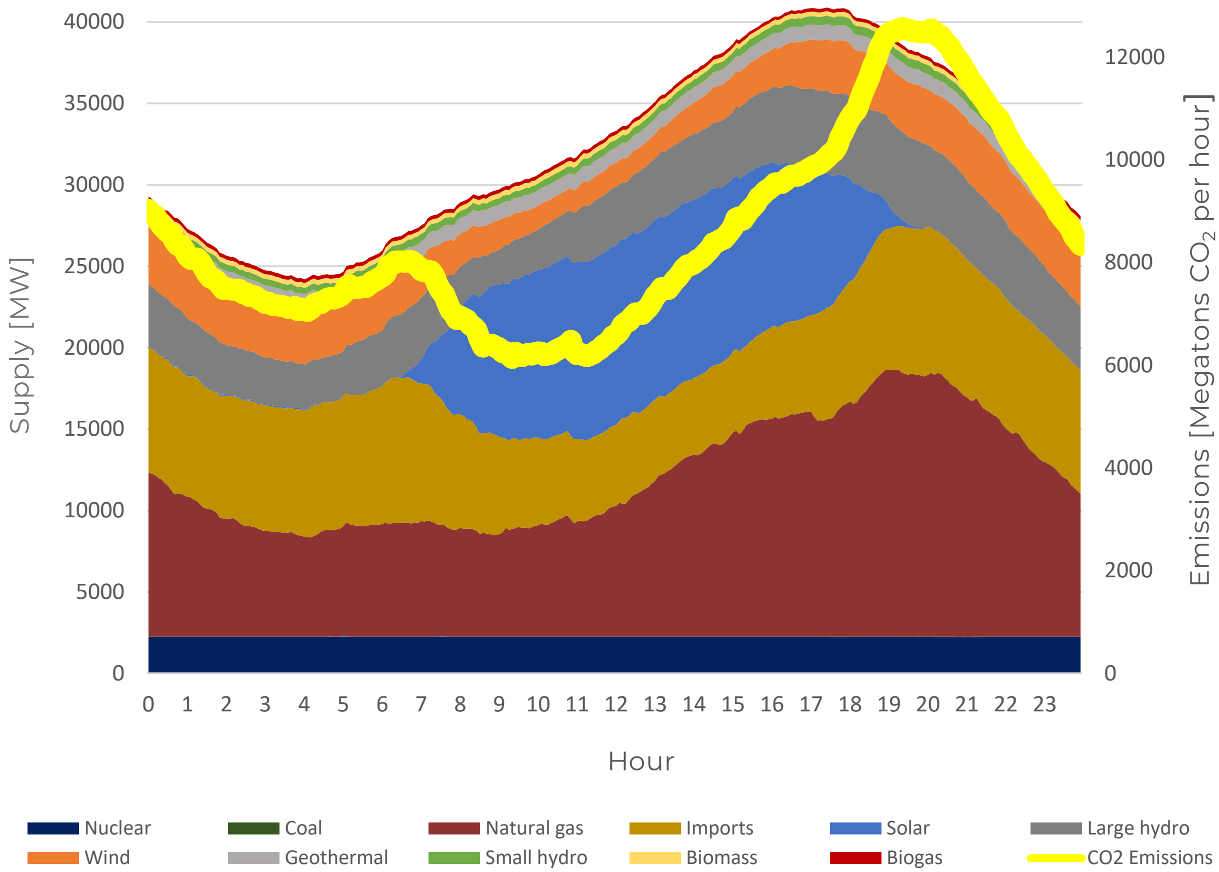


Figure 4 - Electricity generation and associated CO_2 emissions in California on August 10, 2018

Although small, nuclear power contributes to the constant baseload. Natural gas power plants are the largest generation source and supply the largest portion of the baseload and meet the largest portion of the peak demand at 17:00. Electricity is being imported at all hours of the day; however, it does ramp down as solar comes online between 7:00 and 19:00. Wind generation has the opposite profile as solar, contributing a significant amount of generation at night until the late morning and again in the early evening through the night. Electricity generation from hydro is ramped up to meet the peak demand. The peak in CO_2 emissions occurs between 19:00 and 20:00, around that same time solar generation goes offline, electricity imports peak and generation from natural gas peaks.

The generation sources that were used to meet the annual electric demand of each state in the USA are shown in Figure 4 [7].

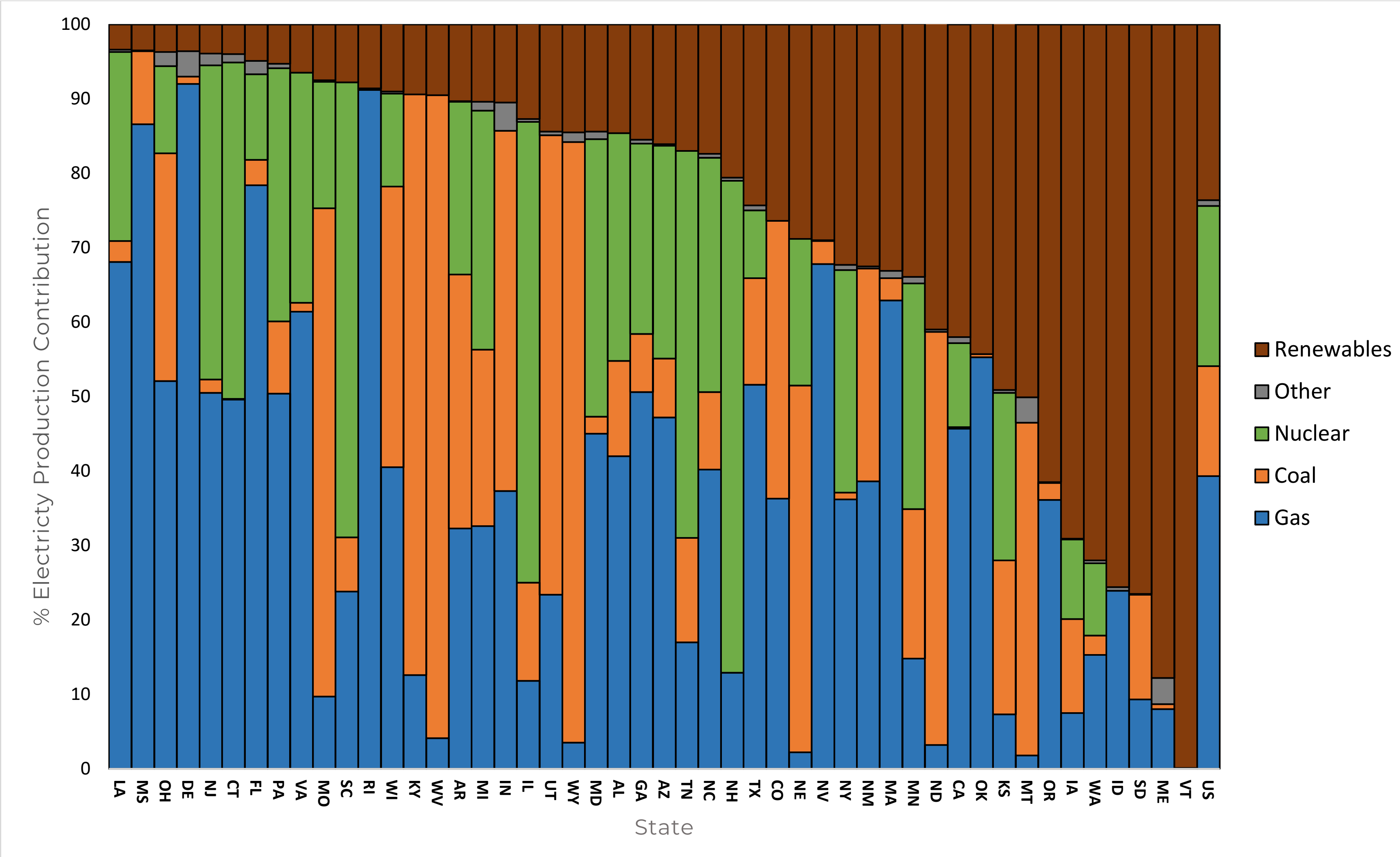


Figure 5 – Electric energy generation sources for each state in the USA

Marginal Emissions

The annual average carbon intensity (tons of CO2 emissions per GWh of electricity generation) of electric grids varies across the USA from 133 tons/GWh in Washington to 298 tons/GWh in West Virginia with a United States Average of 202 tons/GWh (Energy Information Association). The annual average carbon intensity for the California electric grids is 194 tons/GWh. However, when considering the GHG emissions from increasing the load on an electric grid (such as through widespread adoption of electrification) it is important to consider the MER.

Utility grid operators respond to fluctuations in load on the electric grid by increasing or decreasing the amount of power that is purchased from various generation sources. These generation sources that operate on the margin are usually the most expensive and highest emitting power generators in the portfolio and contribute to the MER. As a result, the MER is almost always higher than the average carbon intensity of an electric grid.

MERs calculated by WattTime were used to estimate the indirect CO2 emissions from each heating system. The Watttime calculations are based on a proprietary model that extends the basic methodology used by both Siler-Evans et al. [8] and Callaway et al. [9], but adapted for real-time use. WattTime calculates these marginal operating emission rates in real-time, every 5 minutes using a combination of grid data from the respective independent system operator (ISO) and 5 years of historical continuous emissions monitoring system data (EPA, 2019).

The diversity of power generation assets, distribution infrastructure and operation strategies among the utilities results in a wide range of marginal GHG emissions rates throughout the year across the USA. For example, although the state of Washington has one of the cleanest power generation portfolios in the USA, The Bonneville Power Administration has many natural gas and coal power plants that operate on its margin contributing to an average MER of approximately 920 tons/GWh. The annual average MER for each state in the USA is shown in Figure 5. The annual average marginal CO_2 emissions rates range from approximately 800 pounds of CO_2 per megawatt-hour of electric energy generation in Iowa and California to approximately 2000 pounds of CO_2 per megawatt-hour of electric energy generation in Montana and Wyoming. There is not a strong correlation between the annual average CO_2 intensity and MER across the states. The annual average MER in South Dakota and Utah are within 2% of each other (1943 and 1980 lbs/MWh respectively) but the annual average CO_2 intensity in South Dakota (509 lbs/MWh) is 68% less than the annual average CO_2 intensity in Utah (1595 lbs/MWh). Conversely the annual average MER in Rhode Island is 38% less than the MER in Oklahoma (1063 and 1664 lbs/MWh respectively) but the annual average CO_2 intensity of Rhode Island (879 lbs/MWh) is within 0.2% of the annual average CO_2 intensity of Oklahoma (880 lbs/MWh). Similar variations are found throughout the USA. The annual average CO_2 intensity is not a good indicator of the impact that a change in grid load resulting from the electrification of heating systems would have on CO_2 emissions. For these calculations, the MER should be used instead.

For additional analysis, the states are grouped into regions, as shown in Figure 5. The average MER varies across the six regions in the United States (Pacific, Northeast, Southwest, Rocky Mountains, Southeast, and the Midwest) (Figure 6).

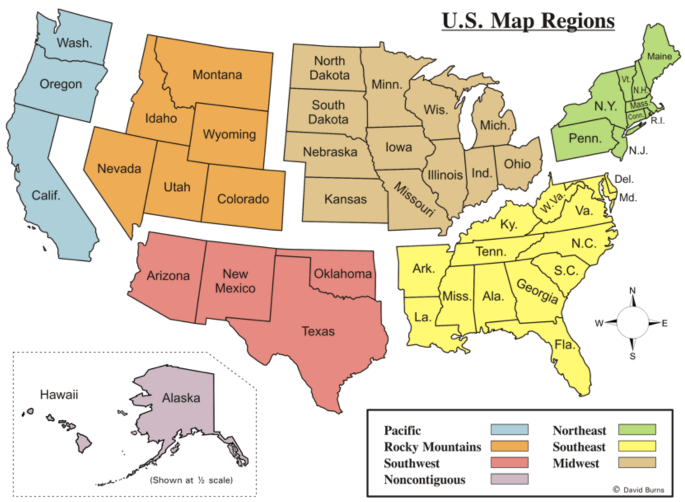


Figure 6 – Map of the six geographic regions

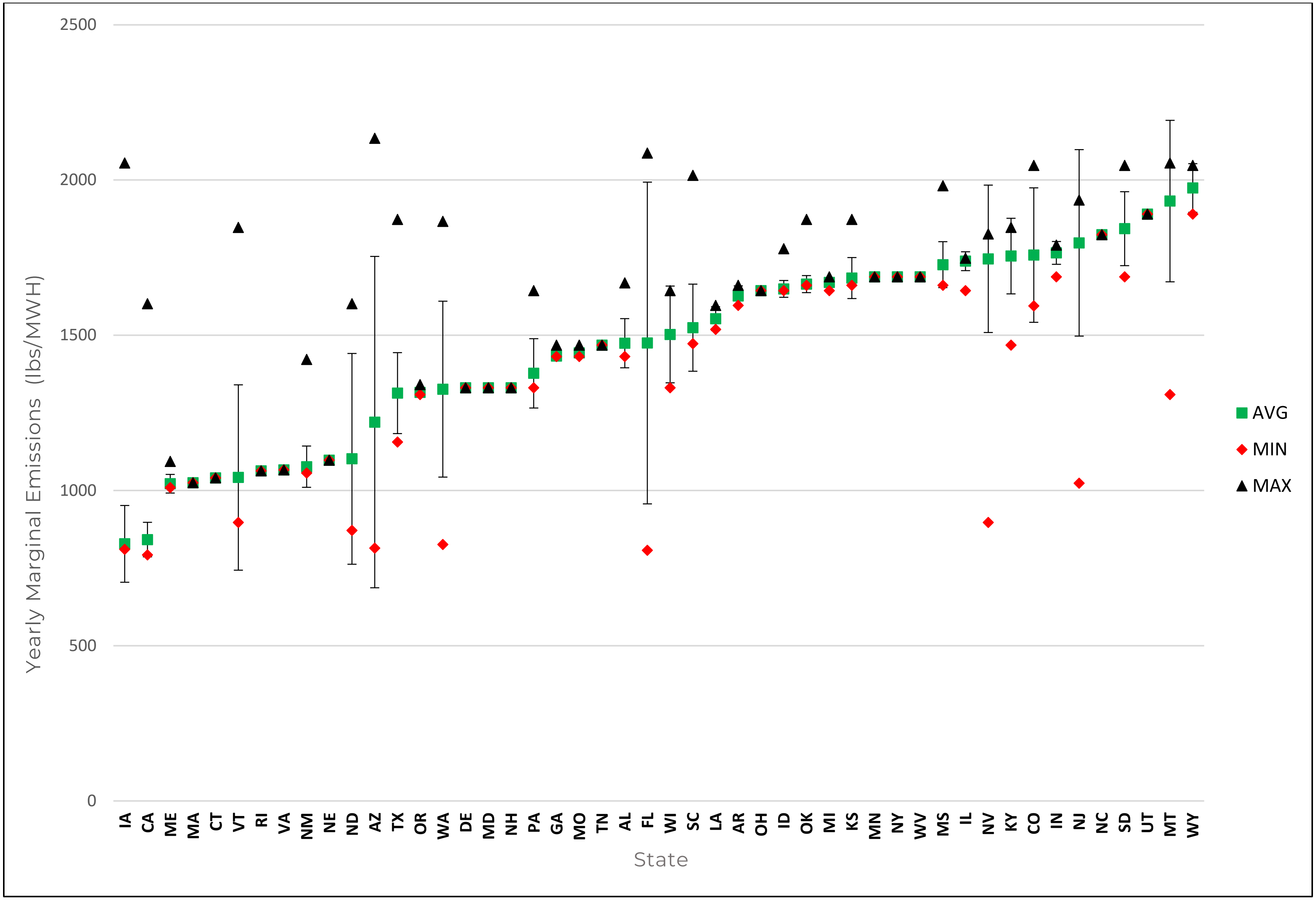


Figure 7 - Annual average MERs for each state. Error bars show one standard deviation.

Although the demand profile and climate contribute to the MER, there is a clear correlation between the portfolio of power generating assets serving the state and the MERs. If the electric grid of a state relies heavily on coal and natural gas power plants, rather than zero-emission energy sources such as renewables and nuclear, the MER will be higher. For example, Figure 4 shows that electric energy in the states in the Pacific region (CA, WA, OR) of the United States is predominantly generated from renewable energy sources with very a moderate amount of natural gas and very little coal. This characteristic translates to lower MERs as shown in Figure 5 and Figure 6. Conversely, Figure 4 shows that the states in the Midwest region generate electric energy from mostly coal and natural gas resulting in much higher MERs shown in Figure 5 and Figure 6

The shape of the daily MER profile varies between the different electric grid territories as well as throughout the year as the climate and load on the electric grid changes with the seasons. The average daily marginal CO2 emissions profile for each month of 2019 are shown in Figure 7 through Figure 10 for four example areas: San Diego (CA), San Francisco (CA) , Helena (MT), and Portland (OR). Of the representative cities, San Diego (CA) and San Francisco (CA) had some of the lowest annual average MERs, Helena (MT) had one of the highest MERs and Portland (OR) had one of the largest annual differences in the annual minimum and maximum MER. The annual average carbon intensity for each state is included in each figure for comparison.

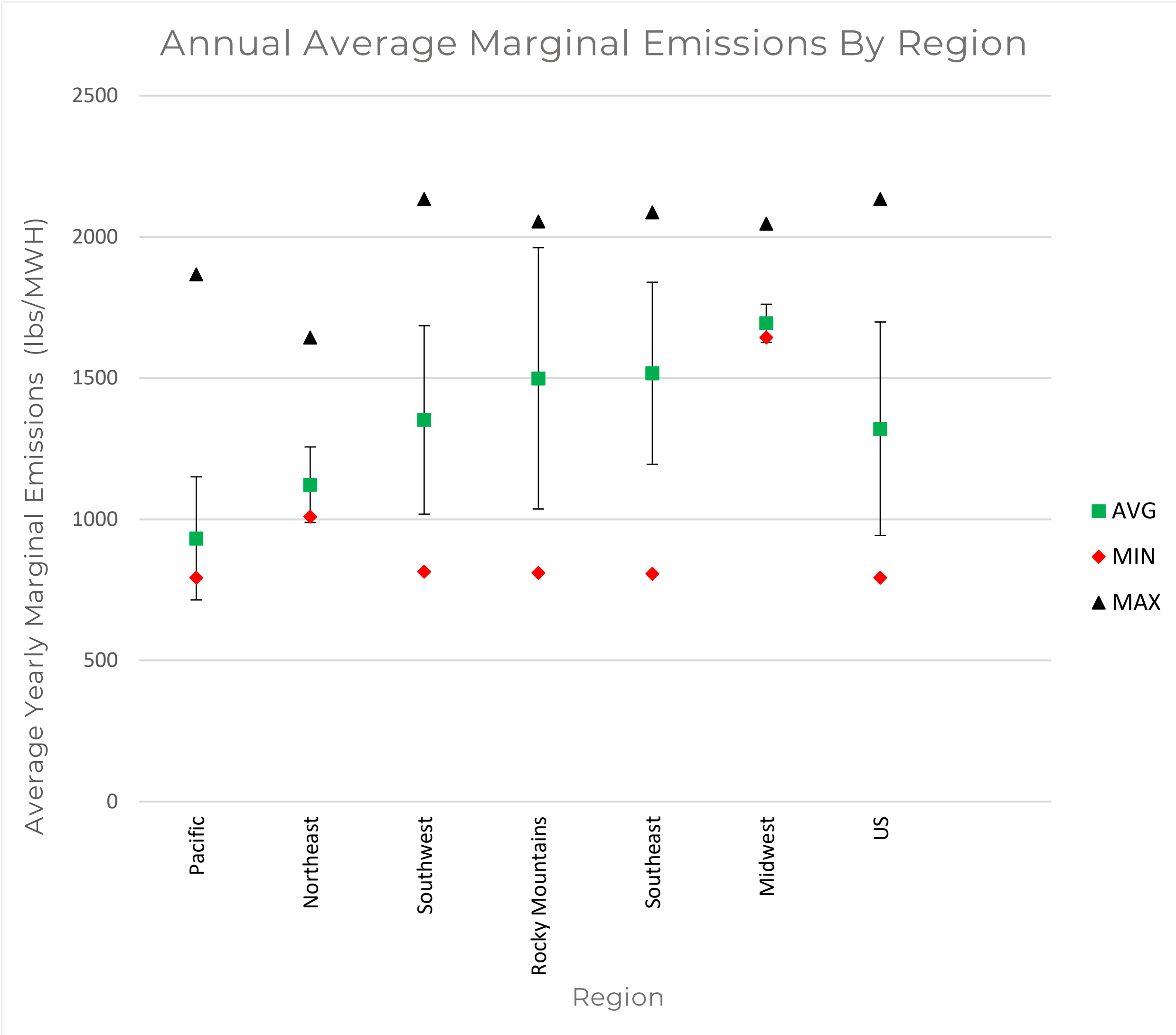


Figure 8 - Annual average MERs for each region. Error bars show one standard deviation.

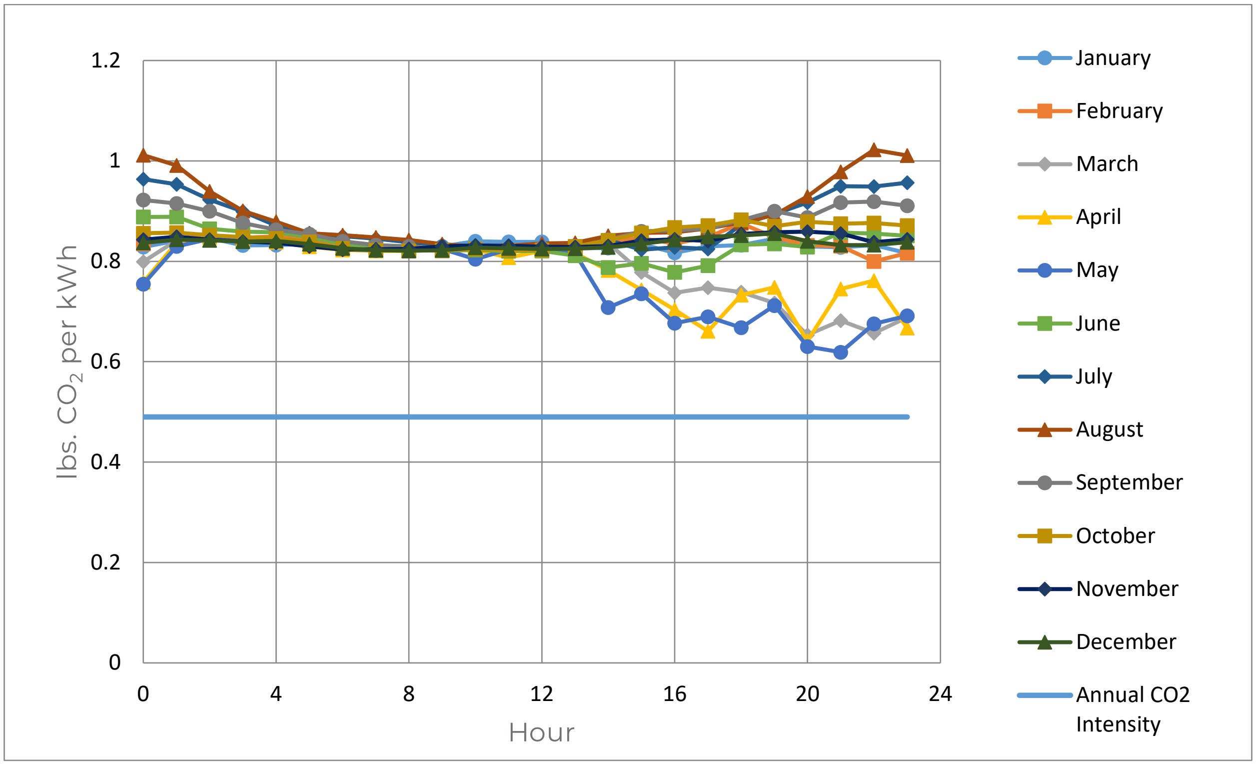


Figure 9 - Average daily marginal CO_2 emissions profile for each month of 2019 in the San Diego, California area

In San Diego, California, the MER does not vary much between 5:00 and 14:00. After 14:00 and until 5:00 the next day the MER fluctuates from hour to hour and from month to month. The annual average MER was 0.814 lbs. CO_2 per kWh, which is 68% higher than the average annual CO_2 intensity of 0.48 lbs. CO_2 per kWh.

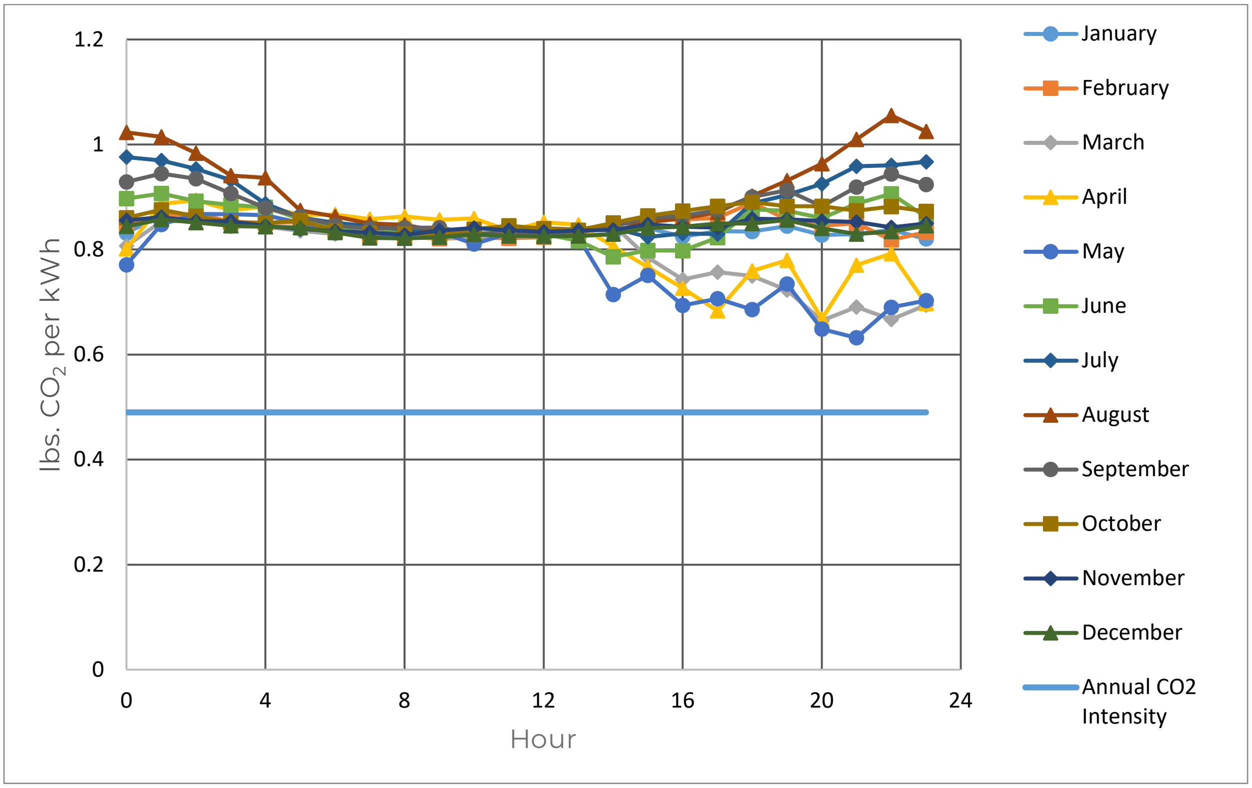


Figure 10 - Average daily marginal CO_2 emissions profile for each month of 2019 in the San Francisco, California area

Both San Diego and San Francisco are served by California Independent Systems Operator (CAISO) grids and have very similar daily profiles. In San Francisco, California, the MER does not vary much between 5:00 and 14:00. After 14:00 and until 5:00 the next day the MER fluctuates from hour to hour and from month to month. The average MER was 0.36 lbs. CO_2 per kWh, which is 64% higher than the average annual CO_2 intensity of 0.484 lbs. CO_2 per kWh.

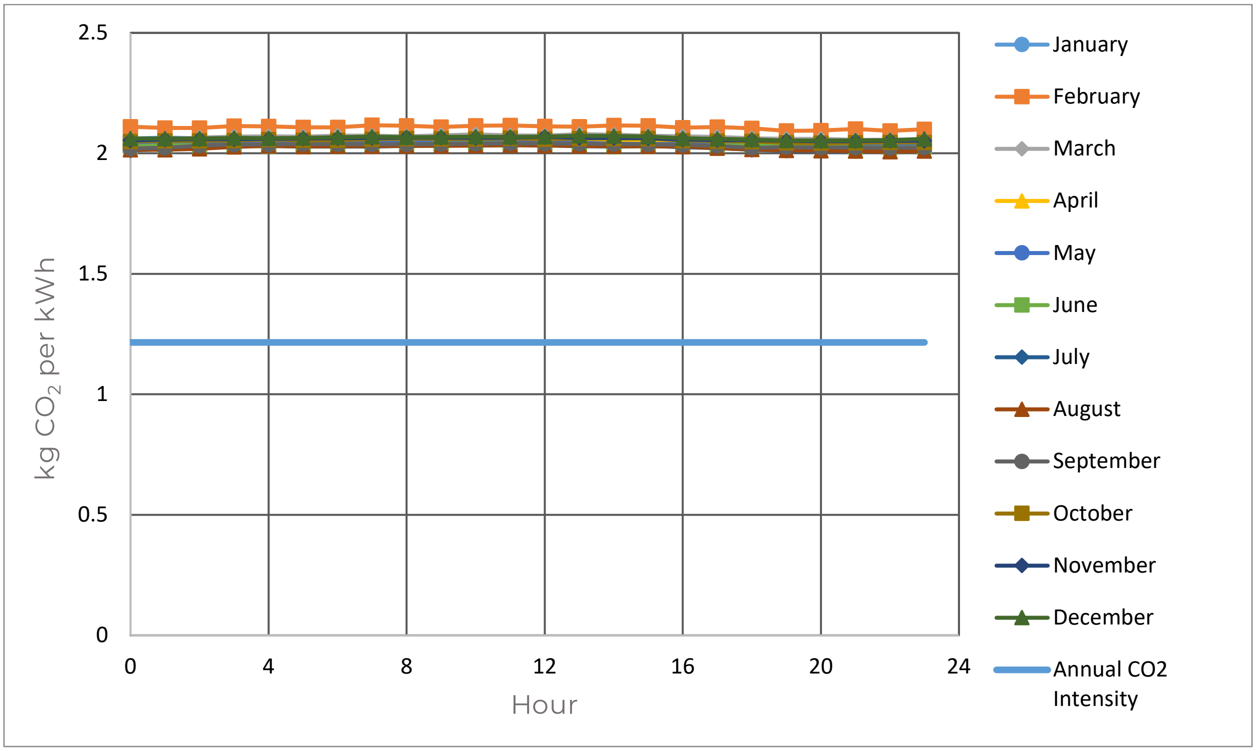


Figure 11 - Average daily marginal CO_2 emissions profile for each month of 2019 in the Helena, Montana area

In Helena, Montana, the MER is consistent throughout the day and only varies slightly from month to month. The average MER was 0.94, which is 71% higher than the average annual CO_2 intensity of 1.21 lbs. CO_2 per kWh.

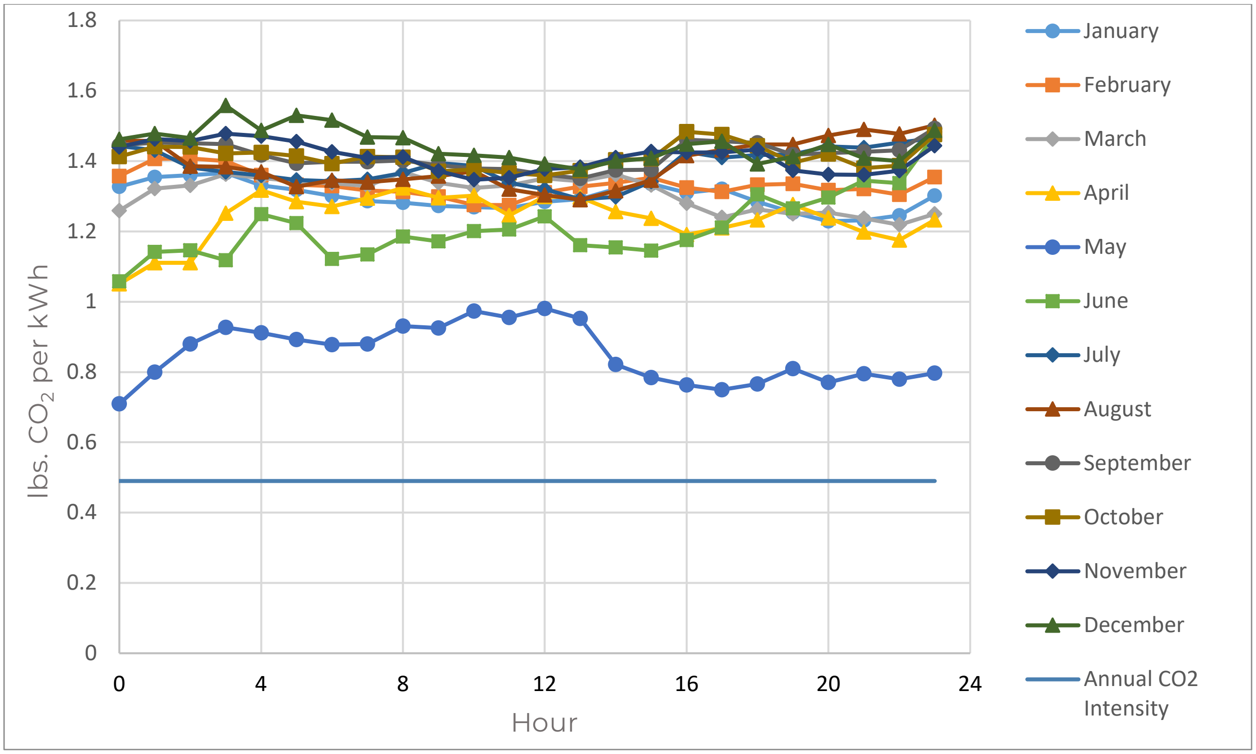


Figure 12 - Average daily marginal CO_2 emissions profile for each month of 2019 in the Portland, Oregon area (excluding January and February).

In Portland, Oregon, the MER fluctuated some throughout the day but varied more significantly from month to month. The average MER was 0.86, which is 291% higher than the average annual CO_2 intensity of 0.484 lbs. CO_2 per kWh.

Representative Cities

Each state was divided into several areas to capture the effect of both climate and electric utility territory on the GHG emissions. Within each unique combination of climate zone and electric utility territory, the most populous city was selected as the representative city for that region. The representative cities were selected based on population to best represent the largest share of population in each area.

To accurately calculate the GHG emissions of a simulated building, the simulated weather data must be paired with corresponding marginal GHG emissions rate data. Weather was simulated in each representative city using historical weather data for the 2019 calendar year. For each location, the historical weather data was paired with historical MERs for the relevant utility territory for the same year. The representative cities that were chosen from the states within the Pacific, Southeast, Midwest, Northeast, Rocky Mountains, Southwest geographic regions are shown in Table 2 through Table 7 respectively.

Table 2 - Representative Cities Residing in the United States Pacific Region

City	State	Climate Zone	Utility Territory	Population	Percent of State
Alturas	CA	5	Bonneville Power Administration	2509	0.006%
Barstow	CA	3	CAISO SP15 Trading Hub	23972	0.061%
Benton	CA	6	CAISO SP15 Trading Hub	280	0.001%
Bishop	CA	4	CAISO SP15 Trading Hub	3746	0.009%
Brawley	CA	2	Imperial Irrigation District	26226	0.066%
Bridgeport	CA	6	CAISO NP15 Trading Hub	575	0.001%
Crescent City	CA	4	PacifiCorp	6805	0.017%
El Centro	CA	2	Imperial Irrigation District	44120	0.112%
Eureka	CA	3	CAISO NP15 Trading Hub	26998	0.068%
Fresno	CA	3	CAISO ZP26 Trading Hub	999101	2.529%
Grass Valley	CA	5	CAISO NP15 Trading Hub	12914	0.033%
Indio	CA	3	Imperial Irrigation District	91240	0.231%
LA Civic Center	CA	3	Los Angeles Dept of Water &	3457	0.009%
Lone Pine	CA	3	Los Angeles Dept of Water &	2035	0.005%
Long Beach	CA	4	Los Angeles Dept of Water &	467354	1.183%
Los Angeles	CA	3	Los Angeles Dept of Water &	3990000	10.099%
Markleeville	CA	6	Sierra Pacific Power Co	210	0.001%
Napa	CA	3	CAISO NP15 Trading Hub	79263	0.201%
Placerville	CA	5	CAISO NP15 Trading Hub	11048	0.028%
Planada	CA	3	CAISO ZP26 Trading Hub	4418	0.011%
Red Bluff	CA	4	Sacramento Municipal Utility	17710	0.045%
Riverside	CA	4	CAISO SP15 Trading Hub	330063	0.835%
Sacramento	CA	3	Sacramento Municipal Utility	508529	1.287%
San Diego	CA	3	CAISO SP15 Trading Hub	1426000	3.609%
San Francisco	CA	3	CAISO NP15 Trading Hub	883305	2.236%
San Jose	CA	3	CAISO NP15 Trading Hub	1030000	2.607%
Santa Maria	CA	3	CAISO ZP26 Trading Hub	107408	0.272%
South Lake	CA	4	Sierra Pacific Power Co	22036	0.056%
Stockton	CA	3	CAISO NP15 Trading Hub	311178	0.788%
Truckee	CA	3	Sierra Pacific Power Co	16561	0.042%
Turlock	CA	3	Turlock Irrigation District	73504	0.186%
Yreka	CA	5	PacifiCorp	7556	0.019%
Bend	OR	5	PacifiCorp West	97590	2.314%
Klamath Falls	OR	5	PacifiCorp West	21536	0.511%
La Grande	OR	5	Bonneville Power Administration	13271	0.315%
Medford	OR	4	PacifiCorp West	82347	1.952%
Portland	OR	4	Bonneville Power Administration	653115	15.484%
Colville	WA	6	Avista Corp	4831	0.063%
Ellensburg	WA	5	Puget Sound Energy Inc	20977	0.275%
Kennewick	WA	5	Bonneville Power Administration	82943	1.089%
Republic	WA	6	Bonneville Power Administration	1070	0.014%
Seattle	WA	4	Seattle City Light	744955	9.783%
Spokane	WA	5	Avista Corp	219190	2.878%
Tacoma	WA	4	Puget Sound Energy Inc	216279	2.840%
Vancouver	WA	4	Bonneville Power Administration	183012	2.403%
Yakima	WA	5	PacifiCorp West	93884	1.233%

Table 3 - Representative Cities Residing in the United States Southeast Region

City	State	Climate Zone	Utility Territory	Population	Percent of State Population
Birmingham	AL	3	Southern Co Services Inc	209880	4.28%
Daphne	AL	2	PowerSouth Energy Coop	26506	0.5%
Dothan	AL	3	PowerSouth Energy Coop	68247	1.4%
Huntsville	AL	3	Tennessee Valley Authority	197318	4.0%
Mobile	AL	2	Southern Co Services Inc	189572	3.9%
Fayetteville	AR	3	SPP Reserve Zone 4	86751	2.9%
Fort Smith	AR	4	SPP Reserve Zone 4	87845	2.9%
Little Rock	AR	4	MISO Arkansas	197881	6.6%
Wilmington	DE	4	PJM Mid-Atlantic Region	70635	7.3%
Cape Coral	FL	2	Florida Power & Light	189343	0.9%
Gainesville	FL	2	Gainesville Regional Utilities	133857	0.6%
Jacksonville	FL	2	JEA	903889	4.2%
Miami	FL	1	Florida Power & Light	470914	2.2%
Orlando	FL	2	Progress Energy Florida	285713	1.3%
Pensacola	FL	2	Southern Co Services Inc	52713	0.2%
Spring Hill	FL	2	Seminole Electric Coop Inc	97402	0.5%
Tallahassee	FL	2	Tallahassee FL (City of)	193551	0.9%
Tampa	FL	2	Tampa Electric Co	392890	1.8%
Atlanta	GA	3	Southern Co Services Inc	498044	4.7%
Gainesville	GA	4	Southern Co Services Inc	41464	0.4%
Rome	GA	2	Tennessee Valley Authority	36634	0.3%
Savannah	GA	2	Southern Co Services Inc	145862	1.4%
Bowling Green	KY	4	Tennessee Valley Authority	68401	1.5%
Lexington	KY	4	PJM Western Region	323780	7.2%
Louisville	KY	4	Louisville Gas & Electric Co	602011	13.5%
Madisonville	KY	4	MISO Illinois	3328	0.1%
Lafayette	LA	2	MISO Arkansas	126143	2.7%
New Orleans	LA	2	MISO Louisiana	391006	8.4%
Shreveport	LA	3	MISO Arkansas	188987	4.1%
Baltimore	MD	4	PJM Mid Atlantic Region	619493	10.2%
Oakland	MD	5	PJM Mid Atlantic Region	1825	0.0%
Gulfport	MS	2	Southern Co Services Inc	71870	2.4%
Hattiesburg	MS	3	Southern Co Services Inc	45951	1.5%
Jackson	MS	3	MISO Mississippi	164422	5.5%
Tupelo	MS	3	Tennessee Valley Authority	38206	1.3%
Asheville	NC	4	Progress Energy Carolina West	92452	0.9%
Boone	NC	5	Duke Energy Carolinas LLC	19562	0.2%
Burnsville	NC	6	Tennessee Valley Authority	61203	0.6%
Charlotte	NC	3	Duke Energy Carolinas LLC	872498	8.3%
Greenville	NC	3	PJM Southern Region	93137	0.9%
Raleigh	NC	4	Duke Energy Carolinas LLC	469298	4.5%
Roanoke Rapids	NC	4	PJM Southern Region	14495	0.1%
Waynesville	NC	4	Tennessee Valley Authority	10112	0.1%
Charleston	SC	3	South Carolina Electric & Gas Co	800198	15.5%
Florence	SC	3	South Carolina Public Service Authority	37625	0.7%
Rock Hill	SC	3	Duke Energy Carolinas LLC	74309	1.4%
Memphis	TN	3	Tennessee Valley Authority	650618	9.5%
Nashville	TN	4	Tennessee Valley Authority	692587	10.1%
Big Stone Gap	VA	4	Louisville Gas & Electric Co	5218	0.1%
Roanoke	VA	4	PJM Western Region	99648	1.2%
Virginia Beach	VA	4	PJM Southern Region	442707	5.2%
Charleston	WV	4	PJM Western Region	47215	2.6%
Morgantown	WV	5	PJM Mid-Atlantic Region	30955	1.7%
Parkersburg	WV	4	PJM Mid-Atlantic Region	29675	1.7%
Wheeling	WV	5	PJM Western Region	26771	1.5%

Table 4 - Representative Cities Residing in the United States Midwest Region

City	State	Climate Zone	Utility Territory	Population	Percent of State Population
Des Moines	IA	5	MISO Illinois	216853	6.87%
Fort Dodge	IA	6	SPP Reserve Zone 5	24098	0.8%
Monticello	IA	5	MISO Minnesota	3885	0.1%
Sioux City	IA	5	SPP Reserve Zone 5	82396	2.6%
Waterloo	IA	6	MISO Minnesota	67798	2.1%
Belleville	IL	4	MISO Illinois	7365	0.1%
Chicago	IL	5	PJM Western Region	2706000	21.4%
Peoria	IL	5	MISO Illinois	111388	0.9%
Evansville	IN	4	MISO Indiana	117963	1.8%
Indianapolis	IN	5	MISO Indiana	876862	13.0%
South Bend	IN	5	PJM Western Region	101860	1.5%
Concordia	KS	5	SPP Reserve Zone 4	4956	0.2%
Dodge City	KS	4	SPP Reserve Zone 2	27329	0.9%
Hays	KS	5	SPP Reserve Zone 2	20852	0.7%
Wichita	KS	4	SPP Reserve Zone 4	389255	13.4%
Detroit	MI	5	MISO Michigan	672662	6.7%
Escanaba	MI	6	MISO Minnesota	12181	0.1%
Garfield	MI	6	MISO Michigan	17710	0.2%
Houghton City	MI	7	MISO Minnesota	7993	0.1%
Kalamazoo	MI	5	PJM Western Region	76545	0.8%
Duluth	MN	7	MISO Minnesota	85884	15.2%
Minneapolis	MN	6	MISO Minnesota	425403	75.4%
Cameron	MO	5	Associated Electric Coop Inc	9703	0.2%
Hannibal	MO	5	MISO Illinois	75959	1.2%
Kansas City	MO	4	SPP Reserve Zone 4	491918	8.0%
Rolla	MO	4	Associated Electric Coop Inc	20390	0.3%
St. Joseph	MO	5	SPP Reserve Zone 5	75959	1.2%
St. Louis	MO	4	MISO Illinois	318069	5.2%
Bismarck	ND	6	MISO Minnesota	73112	9.6%
Fargo	ND	7	MISO Minnesota	124844	16.4%
Omaha	NE	5	SPP Reserve Zone 1	468262	24.2%
Cincinnati	OH	5	PJM Western Region	302605	2.6%
Columbus	OH	4	PJM Western Region	892533	7.6%
Aberdeen	SD	6	MISO Minnesota	28562	3.2%
Brookings	SD	5	SPP Reserve Zone 5	24509	2.8%
Rapid City	SD	6	WAPA Rocky Mountain Region	75443	8.5%
Sioux Falls	SD	6	SPP Reserve Zone 5	89719	10.1%
Merrill	WI	7	MISO Minnesota	9085	0.2%
Milwaukee	WI	6	MISO Minnesota	592025	10.2%

Table 5 - Representative Cities Residing in the United States Northeast Region

City	State	Climate Zone	Utility Territory	Population	Percent of State Population
Bridgeport	CT	5	ISONE Connecticut	144900	4.06%
Boston	MA	5	ISONE Northeast Massachusetts	694583	10.1%
Springfield	MA	5	ISONE Western/Central Massachusetts	155032	2.2%
Worcester	MA	5	ISONE Southeast Massachusetts	185877	2.7%
Portland	ME	6	ISONE Maine	66417	4.9%
Presque Isle	ME	7	ISONE Maine	8998	0.7%
Concord	NH	6	ISONE New Hampshire	43412	3.2%
Manchester	NH	5	ISONE New Hampshire	112525	8.3%
Newark	NJ	4	PJM Mid-Atlantic Region	282090	3.2%
Patterson	NJ	5	PJM Mid-Atlantic Region	145627	1.6%
Albany	NY	5	NYISO Hudson Valley	97279	0.5%
Binghamton	NY	6	NYISO Central	44785	0.2%
Buffalo	NY	5	NYISO West	256304	1.3%
Delmar	NY	6	NYISO Mohawk Valley	8384	0.0%
Hempstead	NY	3	NYISO Long Island	768103	3.9%
Jamestown	NY	6	NYISO West	29315	0.2%
Kingston	NY	6	NYISO Hudson Valley	22950	0.1%
New York City	NY	3	NYISO New York City	8399000	43.2%
Plattsburgh	NY	6	NYISO North	19438	0.1%
Queensbury	NY	6	NYISO Capital	27471	0.1%
Schenectady	NY	5	NYISO Capital	65575	0.3%
Syracuse	NY	5	NYISO Central	142749	0.7%
Utica	NY	5	NYISO Mohawk Valley	60100	0.3%
Yonkers	NY	4	NYISO Hudson Valley	199663	1.0%
Allentown	PA	5	PJM Mid Atlantic Region	121433	0.9%
Bradford	PA	6	PJM Mid Atlantic Region	8361	0.1%
Philadelphia	PA	4	PJM Mid Atlantic Region	1584064	12.4%
Pittsburgh	PA	5	PJM Western Region	301048	2.4%
Providence	RI	5	ISONE Rhode Island	179335	16.9%
Burlington	VT	6	ISONE Vermont	42899	6.9%

Table 6 - Representative Cities Residing in the United Rocky Mountain Region

City	State	Climate Zone	Utility Territory	Population	Percent of State Population
Aspen	CO	7	Public Service Co of Colorado	7365	0.13%
Boulder	CO	5	Public Service Co of Colorado	107353	1.9%
Colorado Springs	CO	5	WAPA Rocky Mountain Region	472688	8.2%
Denver	CO	5	Public Service Co of Colorado	734134	12.7%
Glenwood	CO	6	Public Service Co of Colorado	9972	0.2%
La Junta	CO	4	WAPA Rocky Mountain Region	6998	0.1%
Rangley	CO	6	PacifiCorp East	9972	0.2%
Salida	CO	6	WAPA Rocky Mountain Region	5963	0.1%
Silverton	CO	7	WAPA Rocky Mountain Region	694	0.01%
Trinidad	CO	4	Public Service Co of Colorado	8211	0.1%
Boise	ID	5	Idaho Power Co	228790	12.8%
Bonners Ferry	ID	6	Bonneville Power Administration	2595	0.1%
Coeur d'Alene	ID	5	Avista Corp	51303	2.9%
Elk City	ID	5	Bonneville Power Administration	202	0.01%
Idaho Falls	ID	6	Idaho Power Co	61535	3.4%
Salmon	ID	6	Northwestern Energy	3112	0.2%
Sandpoint	ID	6	Avista Corp	7365	0.4%
Billings	MT	6	Northwestern Energy	109550	10.2%
Glasgow	MT	6	SPP Reserve Zone 5	3328	0.3%
Helena	MT	6	Northwestern Energy	32315	3.0%
Kalispell	MT	6	Bonneville Power Administration	23938	2.2%
Miles City	MT	6	MISO Minnesota	8393	0.8%
Henderson	NV	5	Sierra Pacific Power Co	310390	10.1%
Las Vegas	NV	3	Nevada Power Co	644644	20.9%
Pahrump	NV	5	Nevada Power Co	28973	0.9%
Logan	UT	3	PacifiCorp East	51619	1.6%
Salt Lake City	UT	5	PacifiCorp East	200591	6.3%
St. George	UT	6	PacifiCorp East	87178	2.7%
Casper	WY	6	PacifiCorp East	57461	9.9%
Cheyenne	WY	6	WAPA Rocky Mountain Region	63957	11.1%
Jackson	WY	5	WAPA Rocky Mountain Region	10429	1.8%
Torrington	WY	7	PacifiCorp East	6701	1.2%

Table 7 - Representative Cities Residing in the United Southwest Region

City	State	Climate Zone	Utility Territory	Population	Percent of State Population
Flagstaff	AZ	5	Arizona Public Service Co	73964	1.02%
Lake Havasu City	AZ	3	WAPA Desert Southwest Region	55090	0.8%
Phoenix	AZ	2	Salt River Project	1660000	22.8%
Prescott Valley	AZ	4	Arizona Public Service Co	45751	0.6%
Sierra Vista	AZ	3	Tucson Electric Power Co	44420	0.6%
Tucson	AZ	2	Tucson Electric Power Co	545975	7.5%
Willow	AZ	4	Salt River Project	3023	0.0%
Yuma	AZ	2	Arizona Public Service Co	97908	1.3%
Alamogordo	NM	3	Public Service Co of New Mexico	31701	1.5%
Albuquerque	NM	4	Public Service Co of New Mexico	560218	26.7%
Clovis	NM	4	SPP Reserve Zone 4	38680	1.8%
Hobbs	NM	3	SPP Reserve Zone 3	38277	1.8%
Las Cruces	NM	3	El Paso Electric	103432	4.9%
Santa Fe	NM	5	Public Service Co of New Mexico	84612	4.0%
Guymon	OK	4	SPP Reserve Zone 2	11278	0.3%
Oklahoma City	OK	3	SPP Reserve Zone 4	649021	16.4%
Armillo	TX	4	SPP Reserve Zone 2	199924	0.7%
Beaumont	TX	2	MISO Texas	118428	0.4%
Canadian	TX	3	SPP Reserve Zone 2	2761	0.0%
Dallas	TX	3	ERCOT North	1345000	4.6%
Del Rio	TX	2	ERCOT West	35954	0.1%
El Paso	TX	3	ERCOT West	682669	2.4%
Floydada	TX	4	ERCOT West	2743	0.0%
Houston	TX	2	ERCOT Houston	2326000	8.0%
Kerrville	TX	3	ERCOT South	23729	0.1%
Longview	TX	3	SPP Reserve Zone 4	81647	0.3%
Lubbock	TX	3	SPP Reserve Zone 3	255885	0.9%
Plainview	TX	4	SPP Reserve Zone 3	20442	0.1%
San Antonio	TX	2	ERCOT South	1493000	5.1%
San Augustine	TX	3	MISO Texas	1877	0.0%
Waco	TX	2	ERCOT North	138183	0.5%

Geometry

The baseline building that was modeled in EnergyPlus was a single-family building with 2,400 ft^2 of conditioned space 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 17.

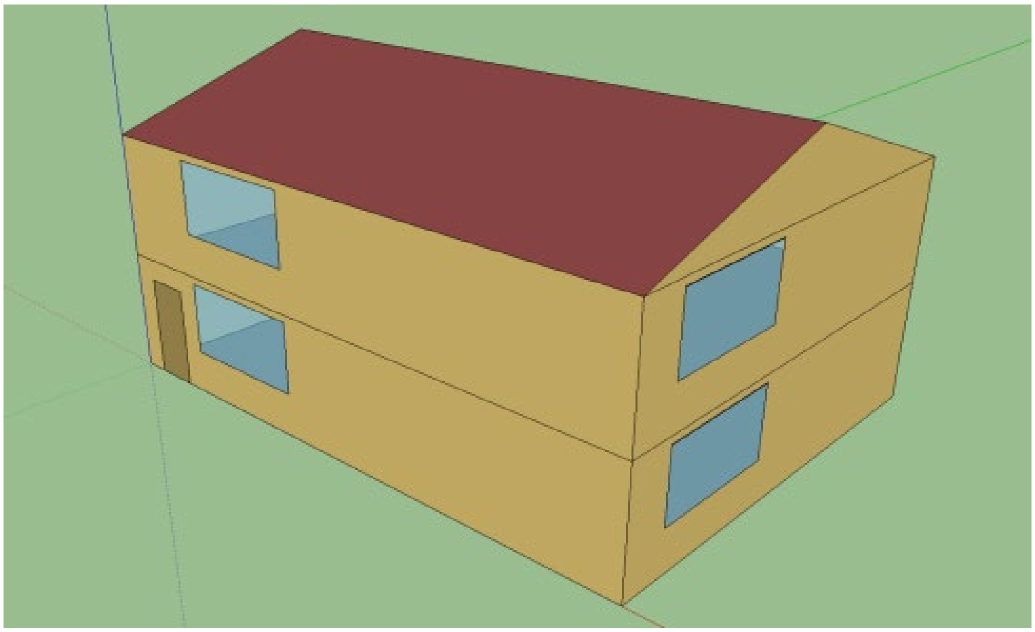


Figure 13 *- Rendering of the single-family building modeled in EnergyPlus*

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. The building was configured to represent new construction with R-13 insulation in the walls and R-19 insulation in the ceiling.

HVAC Systems

The modeled building was simulated with five different HVAC systems described in Table 8.

HVAC System			Cooling		Heating	
			SEER	COP	HSPF	COP
1	Single Speed Air Conditioner/Gas Furnace	(SS AC/GF)	14	3.5	-	-
2	Single Speed Electric Heat Pump	(SS EHP)	14	3.4	8.2	3.5
3	Variable Speed Electric Heat Pump	(VS EHP)	19.75	4.0	10	3
4	Single Speed Dual-fuel Heat Pump	(SS DF HP)	14	3.8	8.5	3.8
5	Variable Speed Dual-fuel Heat Pump	(VS DF HP)	20.5	4.0	10	3.4

Table 8 – Simulated HVAC systems

The single speed air conditioner was simulated with a standard 80% efficient natural gas furnace for heat. The single-family residential building with the single speed air conditioner and gas furnace was used as the baseline to which the other four systems were compared. Performance curves for each HVAC system were fit to manufacturer performance data. The coefficient of performance (COP) of each heat pump at rated indoor air conditions is plotted against outdoor air dry-bulb temperature in Figure 18.

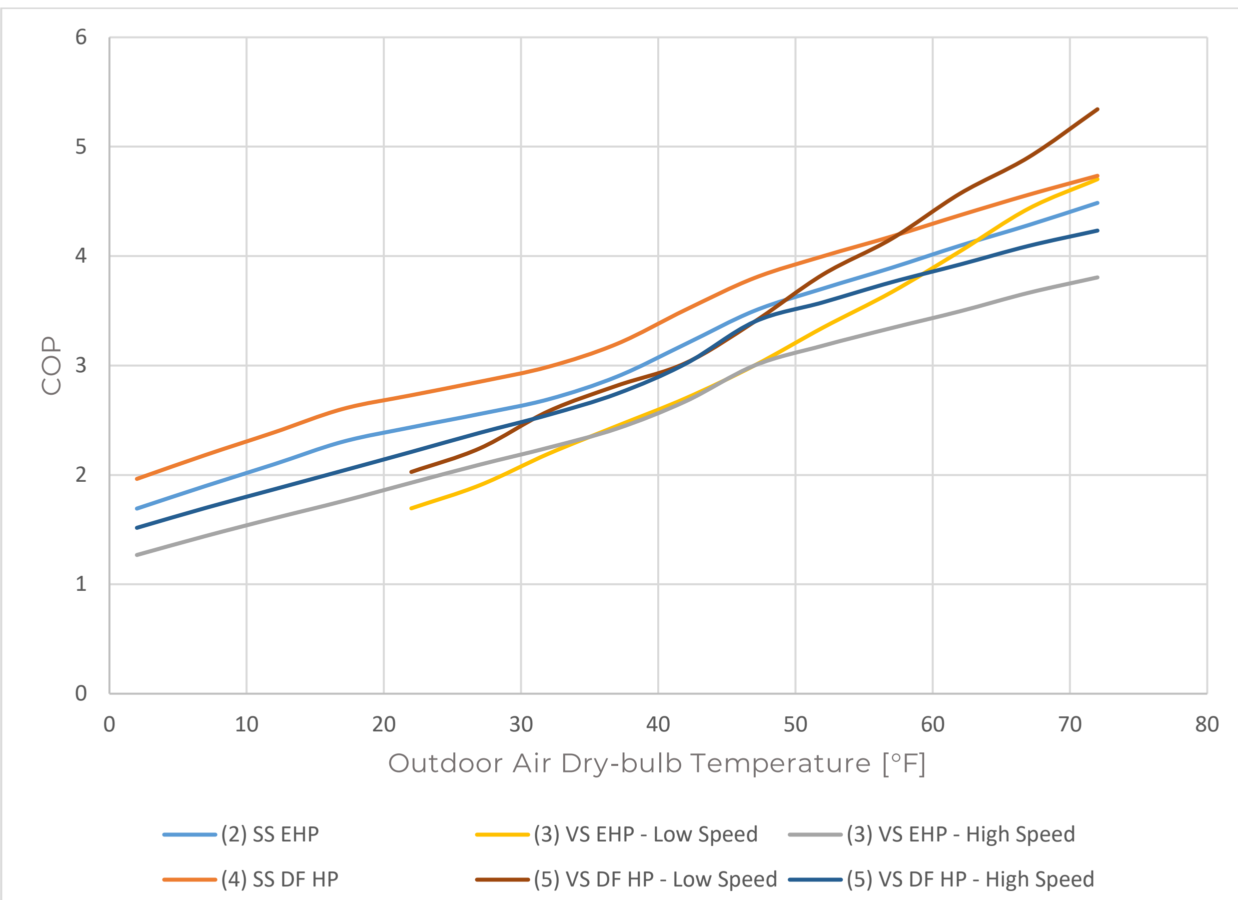


Figure 14 – Heat pump COP at rated indoor air conditions

The COP of each HVAC system increases as outdoor temperature increases. For the variable speed systems, performance data for the system in low speed only goes down to 22 °F because below this temperature it is assumed the heat pump will be operating at full speed.

The heating capacity of each heat pump normalized by rated capacity at 47 °F is plotted against outdoor air dry-bulb temperature in Figure 19.

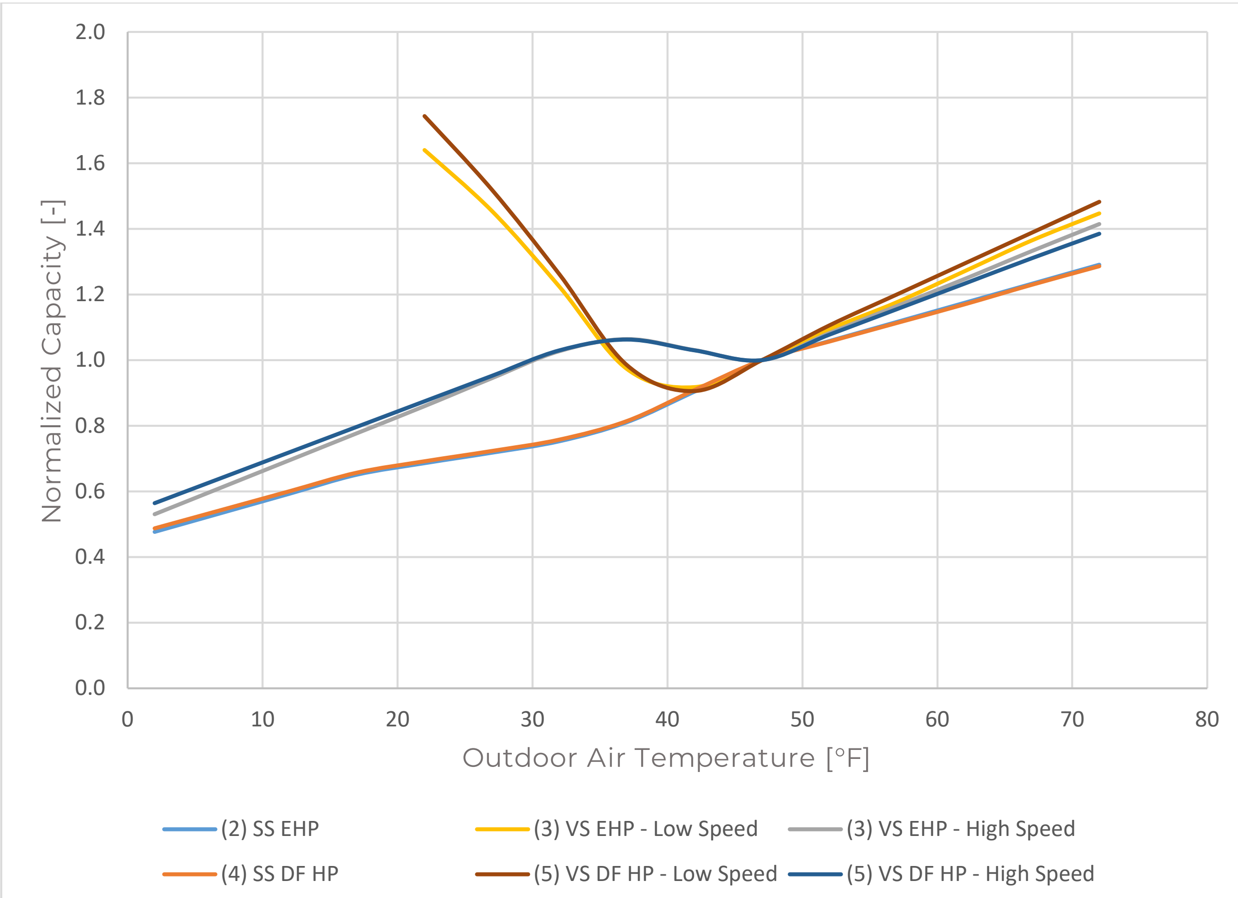


Figure 15 – Heat pump normalized heating capacity

The heating capacity of the single speed heat pumps increases as outdoor temperature increases. The trend is not as simple for variable speed heat pumps. The high speed heating capacity of the variable speed heat pump increases with outdoor air temperature until 37 °F, above which the heating capacity decreases as outdoor air dry-bulb temperature increases until 47 °F, after which the heating capacity increases with outdoor air temperature. The low speed heating capacity of the variable speed heat pump decreases as outdoor air temperature decreases until 42 °F after which it increases with outdoor air dry-bulb temperature. These inflections in the heating capacity curves for variable speed heat pumps at low speed are a consequence of a minimum motor speed imposed by the control system.

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 climates, 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 that is sized for the smaller cooling load, because the heat pump must be sized for the larger heating load.

In a dual-fuel 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 dual-fuel heating system reduces the annual GHG 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.

The rated capacity of the air conditioners and electric heat pumps were sized using design day conditions for each location. The rated capacity of each system was sized using a sizing factor defined as the ratio between the rated capacity and the design day load. Equipment sized with a sizing factor of 1 would have a rated capacity equal to the thermal load of the building at design day conditions. However, if design day conditions are more extreme than the conditions at which the equipment is rated, then the equipment will not have adequate capacity to meet the load since capacity is diminished at more extreme 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 [10]. A sizing factor of 1.4 was used to size each simulated HVAC system.

The heating setpoint was set to 68 °F and the cooling setpoint was set at 74 °F. The all electric heat pumps augment their heating capacity with the auxiliary electric resistance heaters any time the heat pump capacity is insufficient to maintain the indoor air setpoint. For the dual-fuel heating system, 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 electric heat pump operation is suspended and the heating load of the building is met using only the gas furnace. Once the indoor air temperature meets the setpoint temperature the system resets and electric heat pump operation continues. This control strategy simulates the behavior of a typical thermostat installed with dual-fuel heating systems.

CO_2 Emissions

The CO_2 emissions of each simulated case were calculated based on the annual natural gas consumption and the electricity used each hour 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 emissions. Data for the MERs of each utility territory was available at a 5-minute resolution. An hourly average of both the MERs and the Energyplus simulation results was post-processed to calculate emission rates.

RESULTS

Annual CO_2 emissions

Complete and partial electrification of residential heating systems through replacing natural gas furnaces with all-electric and dual-fuel heat pumps had a varied impact on GHG emissions in different parts of the USA. 233 locations across the USA were simulated to capture the effect of electric power generation infrastructure and climate on CO_2 emissions from electrification. The results were then calculated for each state using a population-weighted average. The plots displaying the impact of complete and partial electrification with heat pumps on CO_2 emissions can be found in Figure 20 through Figure 24.

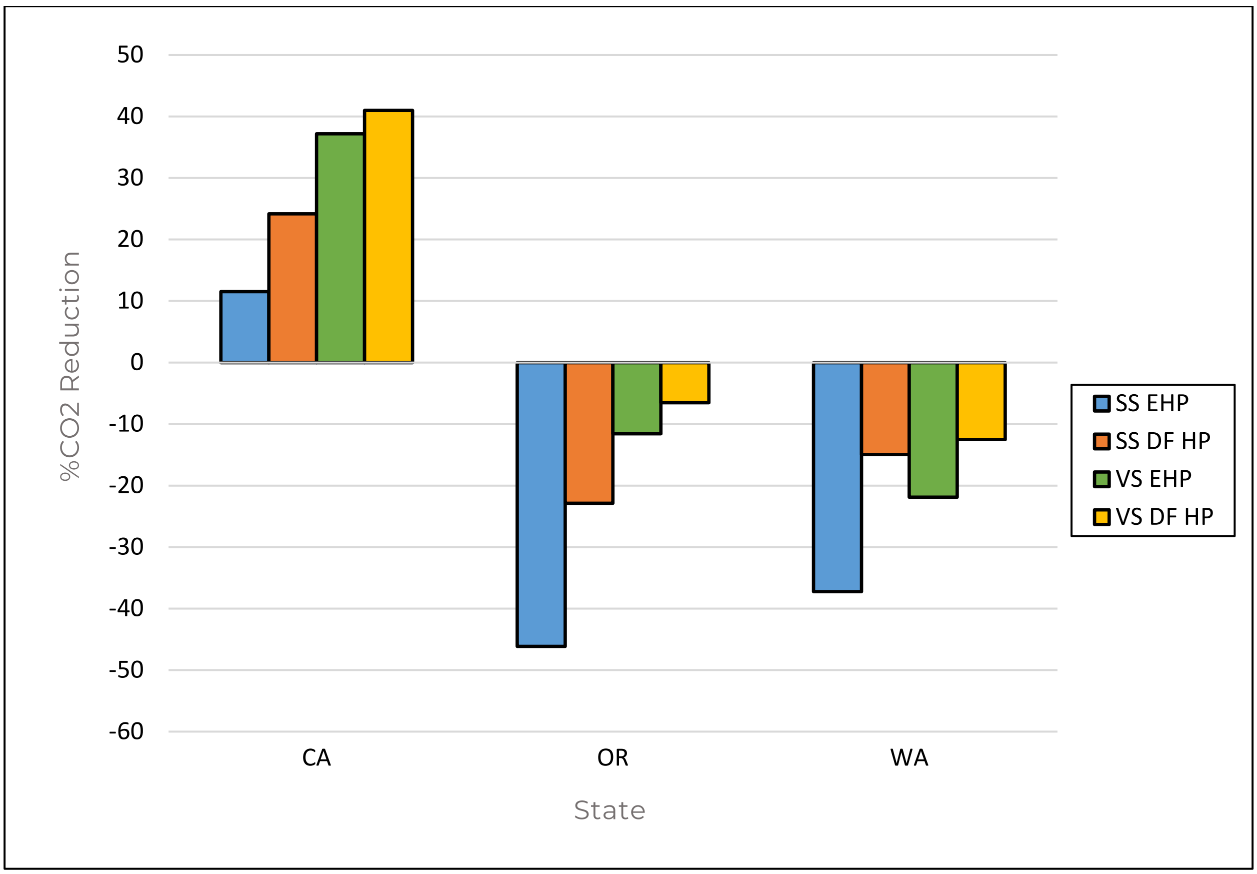


Figure 16 - Average percent CO2 reduction heat pumps compared to gas furnace, Pacific Region

In the pacific region of the USA, the change in CO_2 emissions from heating system electrification varied from state to state. Simulation results for California show a reduction in CO_2 emissions from all four heating systems when compared to the baseline natural gas furnace. The combination of climate and MER in Oregon and Washington State resulted in an increase in CO_2 emissions from all four heating systems. The simulated CO_2 emissions for variable speed heat pumps were consistently lower than the single speed heat pumps for all states in the pacific region. Simulations of the dual-fuel heat pumps resulted in less CO_2 emissions than their all-electric heat-pump counterparts.

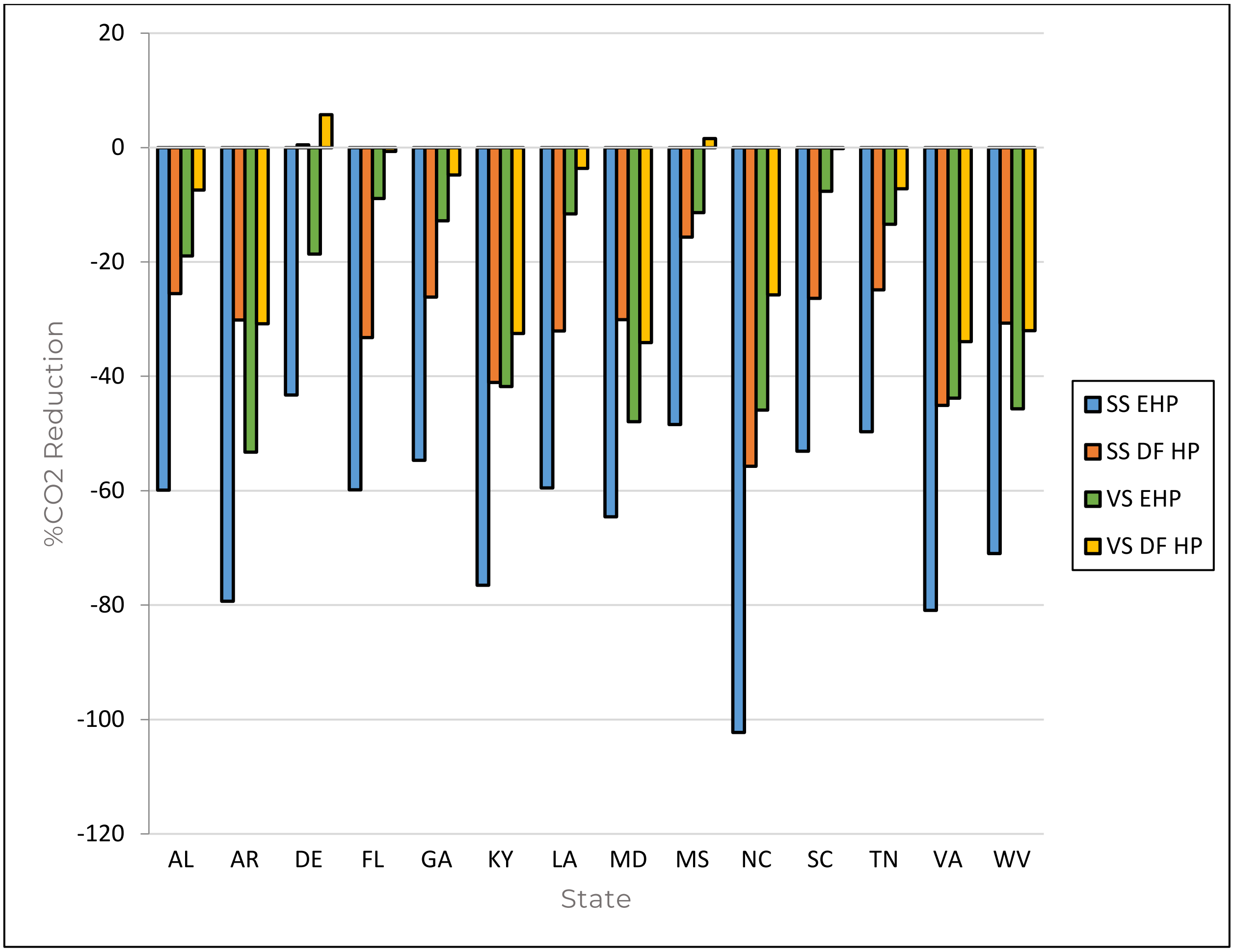


Figure 17 - Average percent CO2 reduction heat pumps compared to gas furnace, Southeast Region

The change in CO_2 emissions from heating system electrification was more consistent in the southeast region of the USA. Except for single- and variable-speed dual-fuel heat pumps in Delaware and the dual-fuel variable-speed heat pump in Mississippi, heating system electrification in the southeastern states resulted in CO_2 emission increases for all four simulated heat pumps. As with the pacific, the variable-speed systems performed consistently better in terms of CO_2 emissions than their single-speed counterparts. Additionally, the dual-fuel systems performed consistently better than their all-electric counterparts.

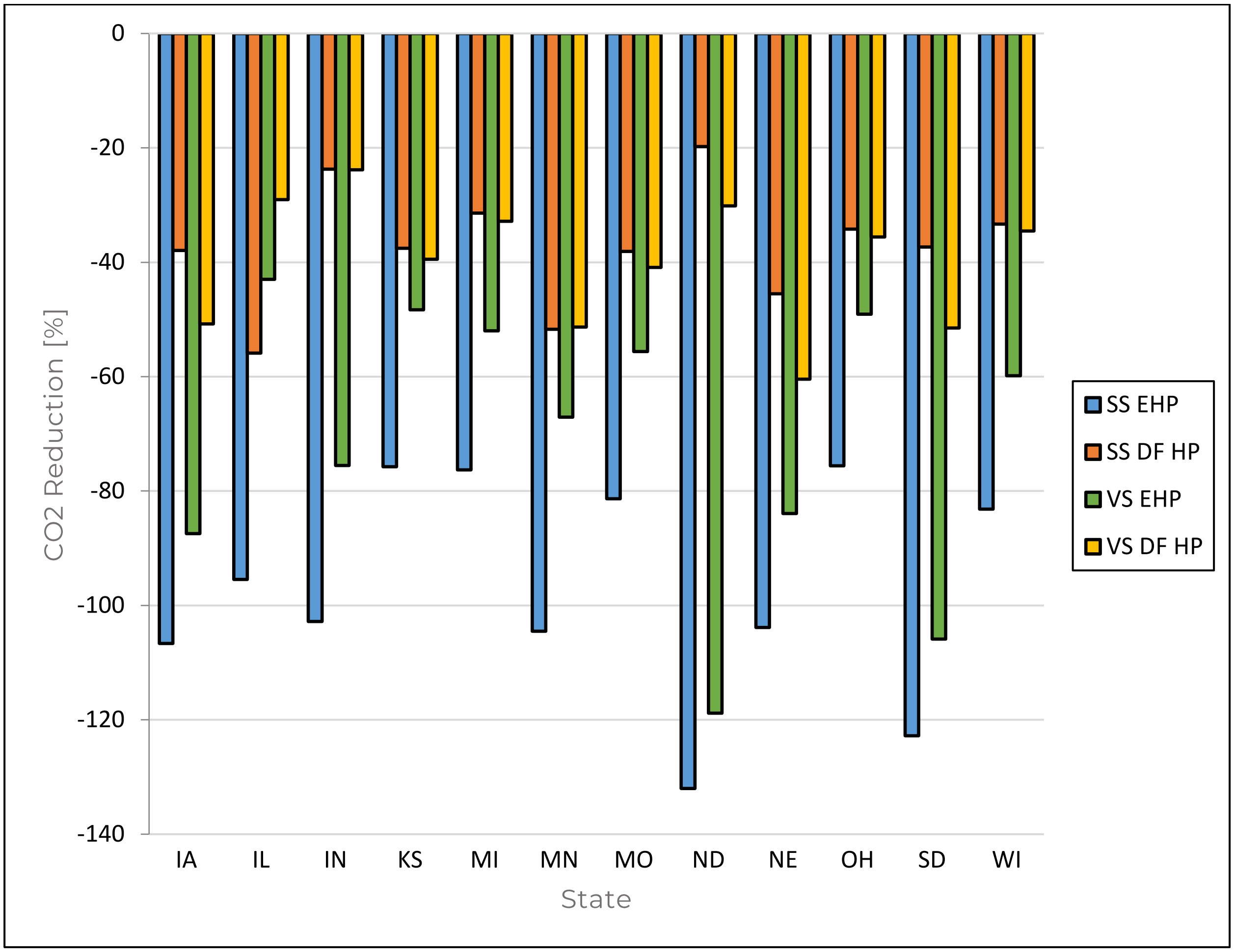


Figure 18 - Average percent CO2 reduction heat pumps compared to gas furnace, Midwest Region

In the Midwest, CO_2 emissions increased from heating system electrification in each state for all four simulated heat pumps. Additionally, the Midwestern states experienced the largest increase in CO_2 emissions in comparison to all other regions. In several states in the Midwest the single-speed dual-fuel heat pump outperformed both variable speed systems in terms of CO_2 emissions. The cold winter climate in this region mean that the heat pumps frequently operate at full speed, reducing the benefit of variable speed systems, and rely on auxiliary heat to meet the heating load. The frequent use of auxiliary heat combined with the regions reliance on coal for electricity production resulted in dual-fuel heat pumps emitting less CO_2 than all-electric heat pumps.

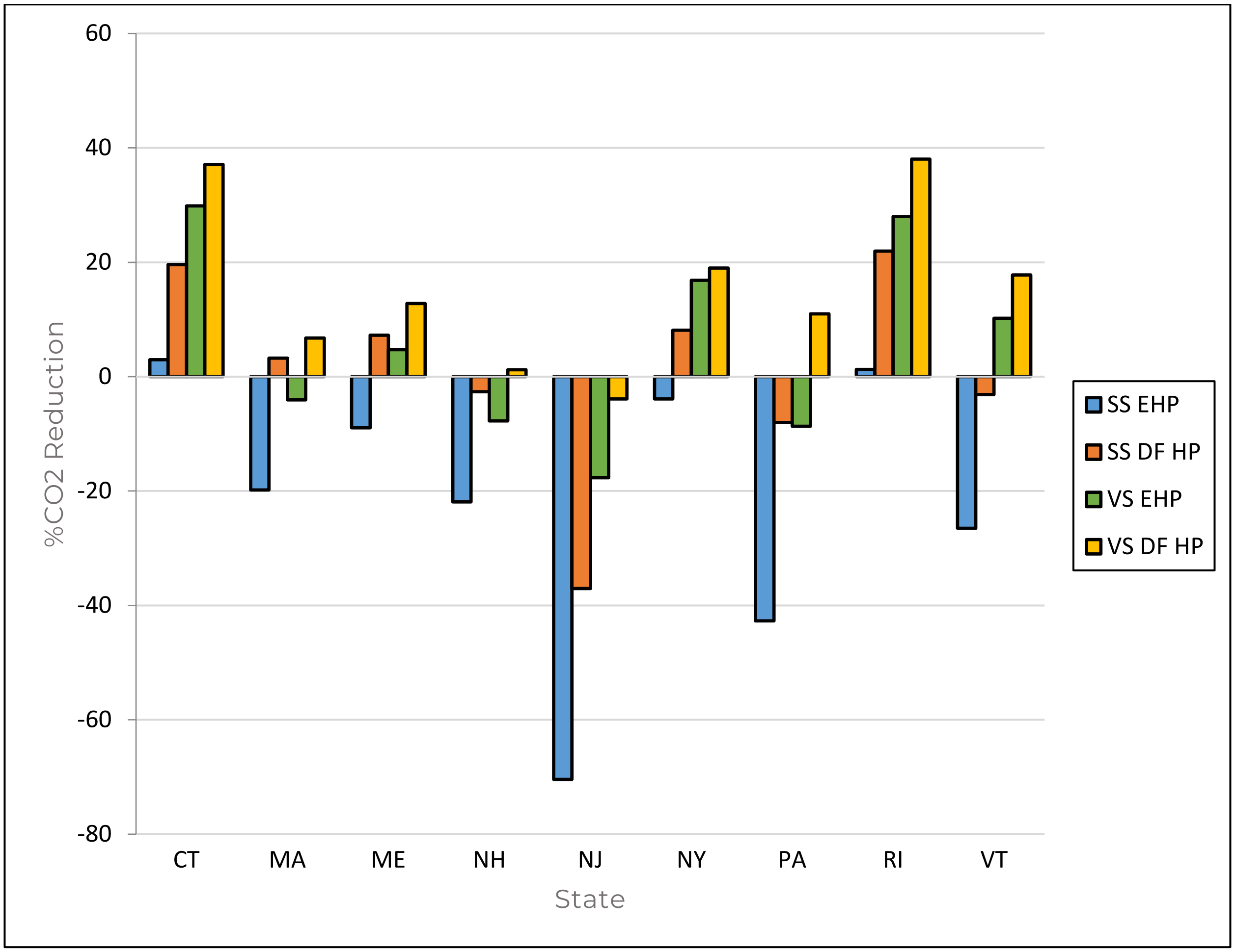


Figure 19 - Average percent CO2 reduction heat pumps compared to gas furnace, Northeast Region

As with the United States Pacific Region, the simulations of states in the Northeast Region predicted mixed CO_2 emission reductions resulting from heating system electrification. CO_2 emissions were reduced in Connecticut and Rhode Island for all heat pumps. Heating system electrification had mixed results in Massachusetts, Maine, New York, Pennsylvania, and Vermont. Lastly, each of the four heat pumps resulted in increased CO_2 increases when compared to a natural gas furnace in New Jersey. Dual-fuel heat pumps achieved greater CO_2 reductions in comparison to the all-electric heat pumps for all states. Additionally, variable-speed systems were advantageous to single-speed systems in reducing CO_2 emissions.

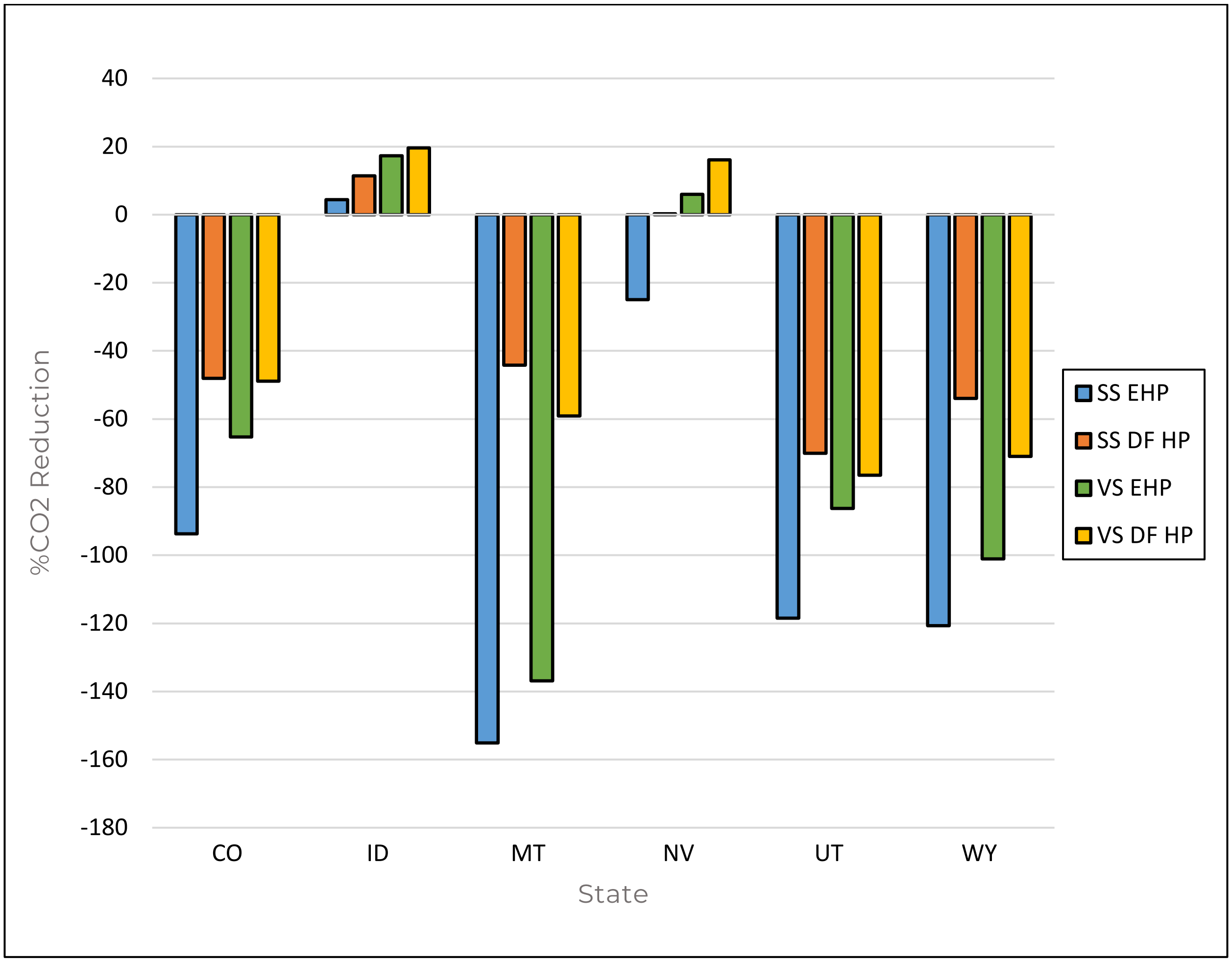


Figure 20 - Average percent CO2 reduction heat pumps compared to gas furnace, Rocky Mountain Region

The change in annual CO_2 emissions from heating system electrification varied among the states in Rocky Mountain Region. Simulations of all-electric heat pumps in Montana predicted the largest percent increase in CO_2 emissions of any state. Idaho was the only state in the region that was predicted to experience a decrease in CO_2 emissions from all four simulated heat pumps. As for the other states, Colorado, Utah, and Wyoming were predicted to increase CO_2 emissions from all four simulated heat pumps. Variable speed heat pumps were predicted to reduce CO_2 emissions in Nevada, but single-speed heat pumps increased CO_2 emissions in the state.

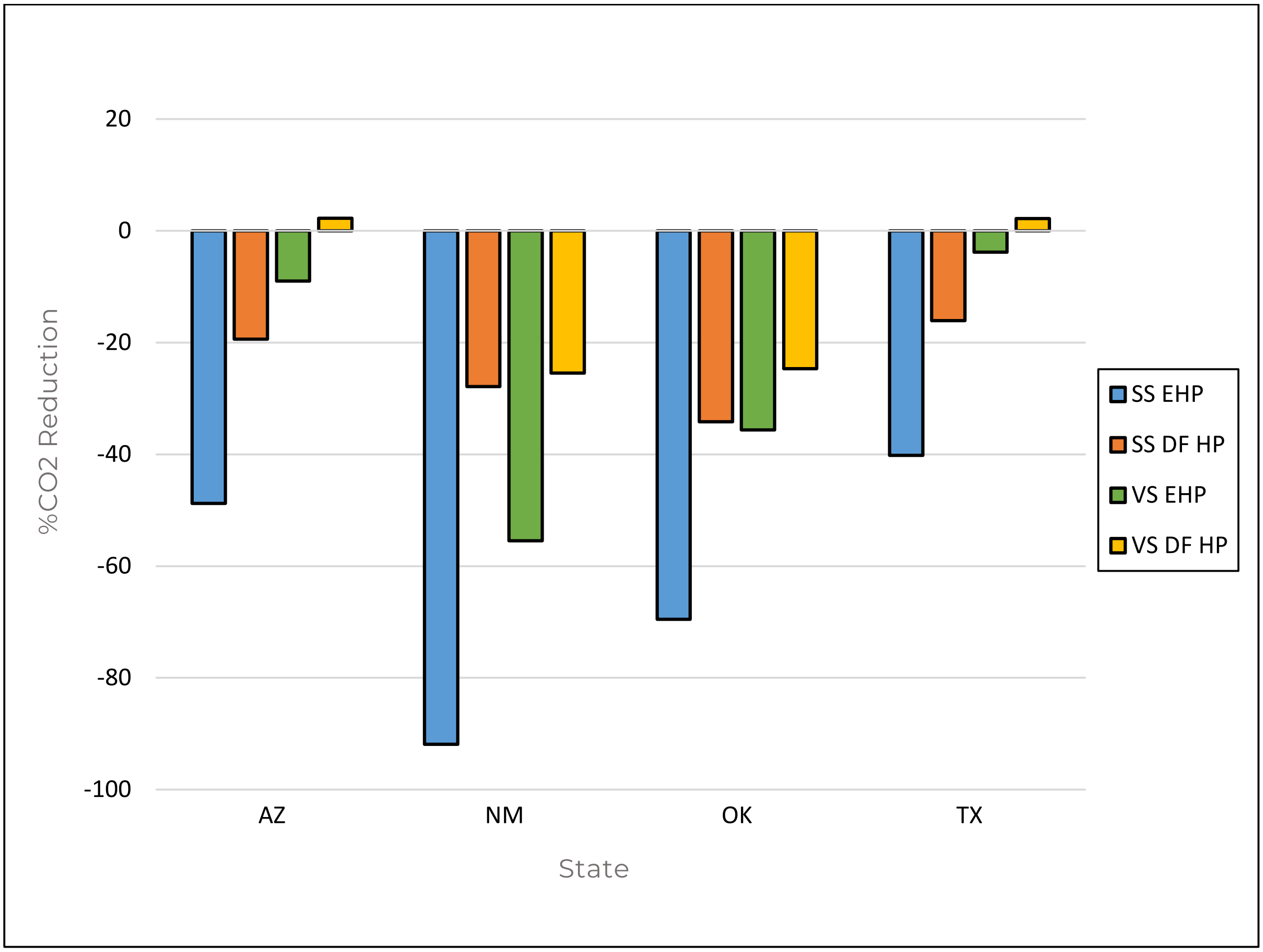


Figure 21 - Average percent CO_2 reduction heat pumps compared to gas furnace, Southwest Region

The change in CO_2 emissions from heating system electrification was consistent in the Southwest Region. Except for variable-speed dual-fuel heat pumps in Arizona and Texas, heating system electrification in the Southwest states resulted in CO_2 emission increases. The reduction in CO_2 emissions achieved by the variable-speed dual-fuel heat pumps in Arizona and Texas was less than 3%. As with the other regions, the variable-speed systems performed consistently better in terms of CO_2 emissions than their single-speed counterparts. Additionally, the dual-fuel systems performed consistently better than their all-electric counterparts.

The distribution of the reduction in annual CO_2 emissions achieved by each heat pump when compared to a natural gas furnace is shown in Figure 22.

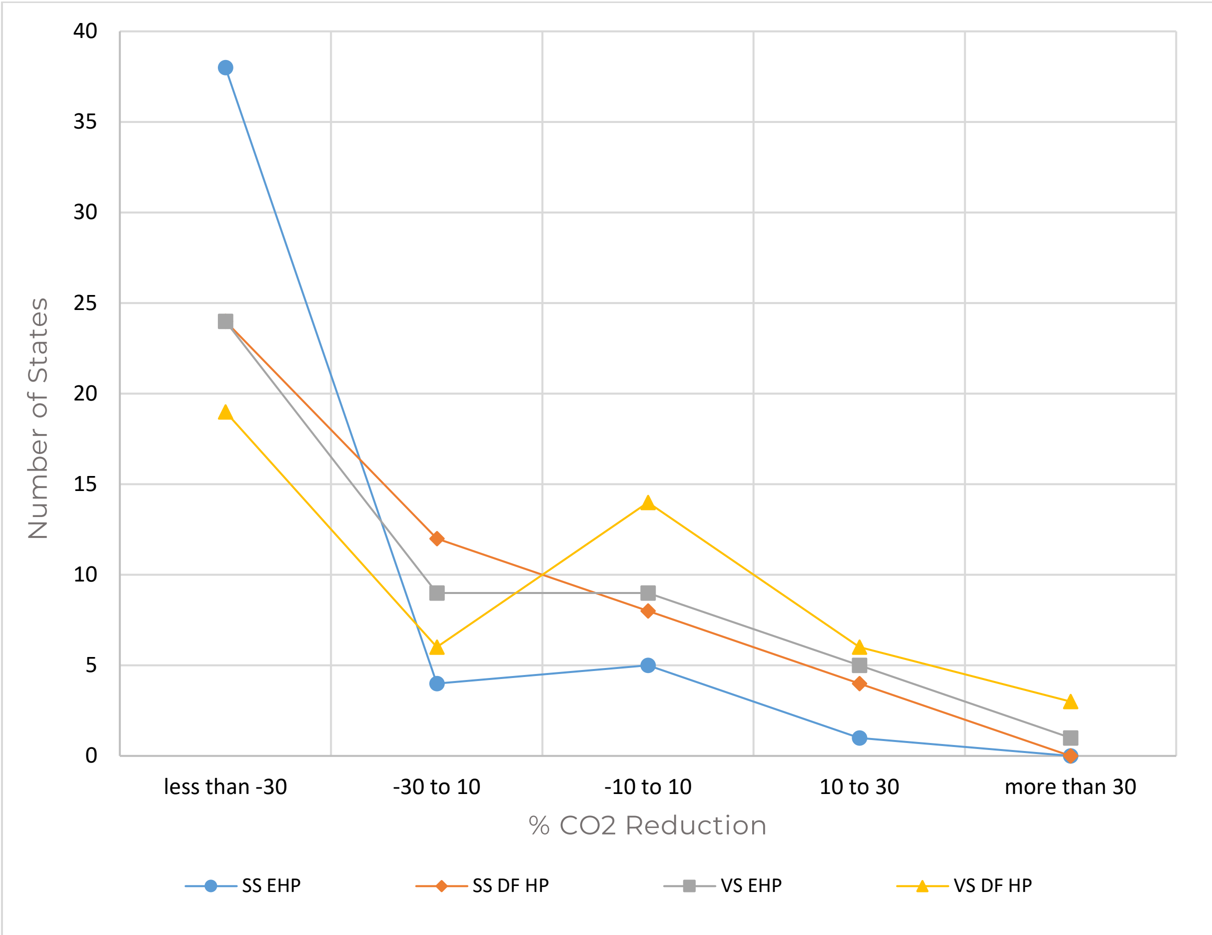


Figure 22 – Number of states that binned by the CO2 emissions reduction achieved by each heat pump when compared to a natural gas furnace

The number of states in which each simulated heat pump reduced CO_2 emissions when compared to a natural gas furnace is shown in Figure 23.

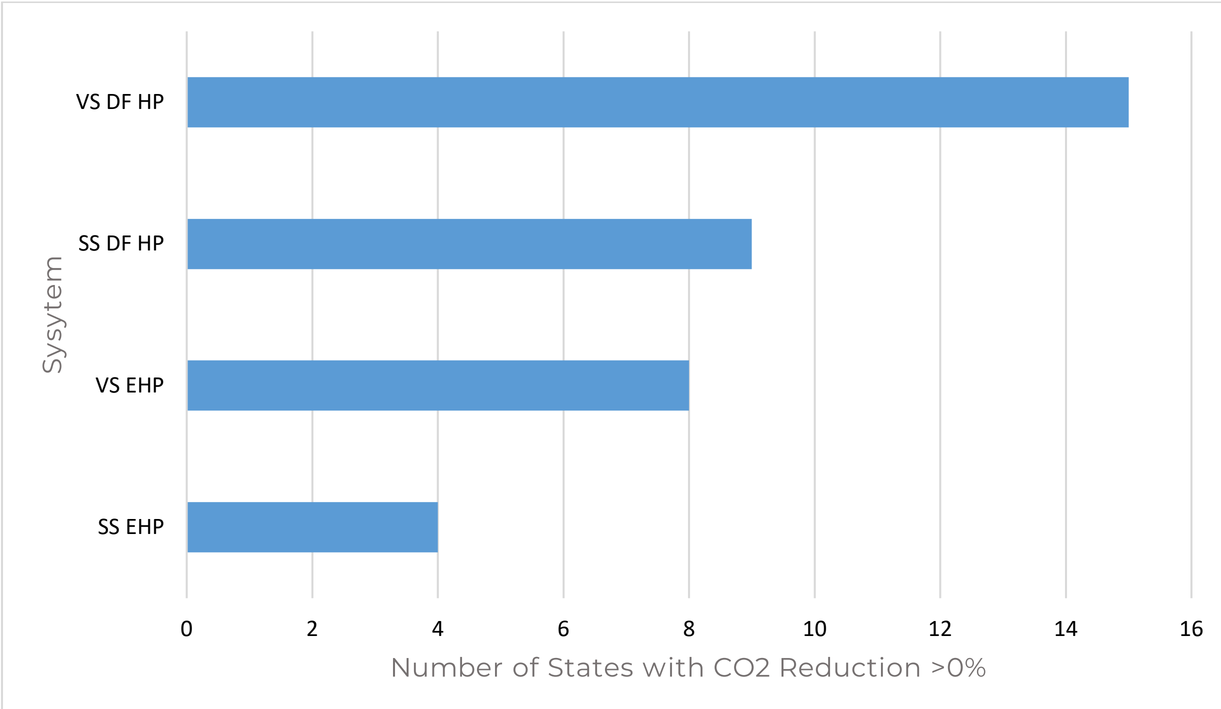


Figure 23 - Number of states that reduced CO2 emissions when each simulated heat pump was compared to a natural gas furnace

The impact on CO_2 emissions that each heat pump has is largely dependent on the local climate and the makeup of the electric grid. As shown in Figure 16 through Figure 21, the heat pump that results in the largest reduction in CO_2 emissions varies between states in the USA. Figure 24 compares the estimated annual CO_2 emissions of the single speed dual-fuel heat pump to that of the variable-speed electric heat pump plotted against the percent contribution of coal and renewable sources in each state.

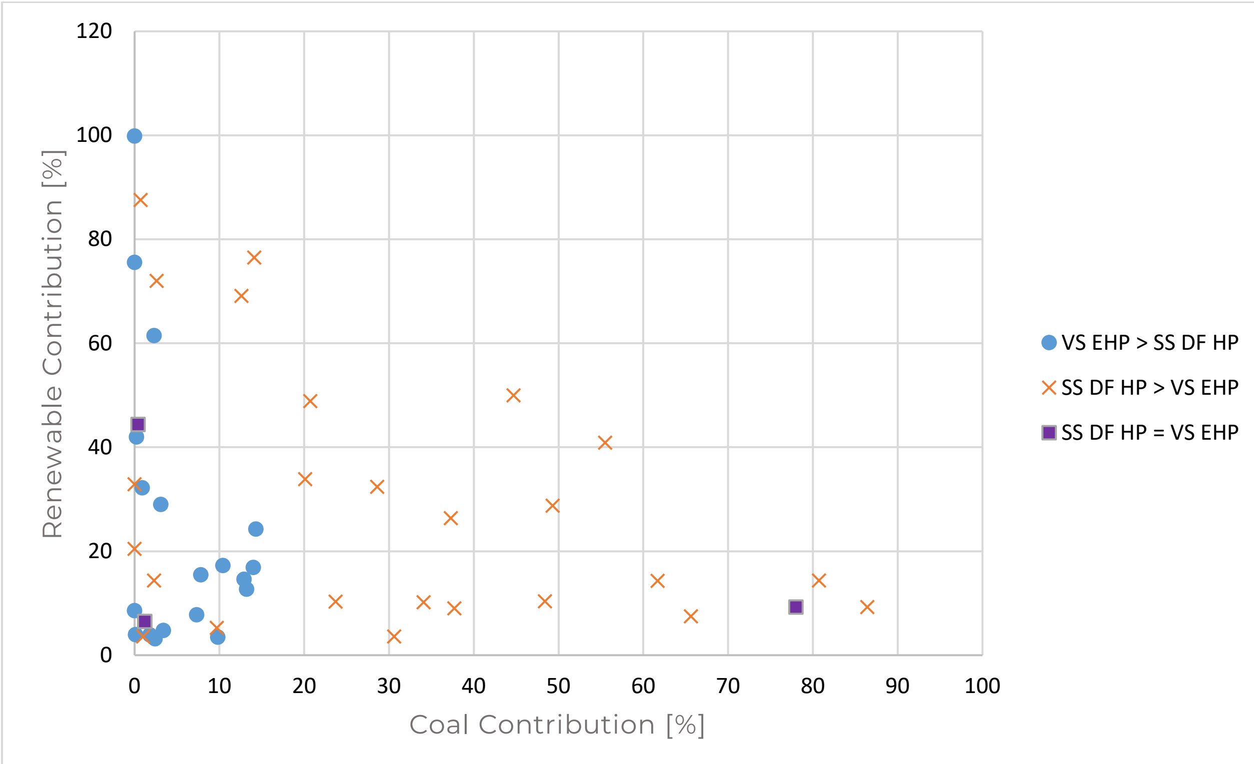


Figure 24 – Comparison of the estimated reductions in CO_2 emissions of the single speed dual-fuel heat pump in each state

The single-speed dual-fuel heat pump emitted less CO_2 annually than the variable-speed electric heat pump in the 17 states where more than 15% of the electric power was generated through the combustion of coal except for 1 state where they were approximately equal. In the 31 states where less than 15% of the electric power was generated through the combustion of coal, the variable-speed electric heat pump emitted less CO_2 annually than the single-speed dual-fuel heat pump in 9 states, the single-speed dual-fuel heat pump emitted less CO_2 annually than the variable-speed electric heat pump in 20 states, and emissions from the two heat pumps were approximately equal in 2 states.

Changes to the Electric Grid

In terms of GHG emissions in the USA, an electric grid that relies entirely on the combustion of coal to generate electricity can be considered the worst case scenario and an electric grid that relies entirely on renewable sources to generate electricity can be considered the best case scenario. The GHG emissions of every grid in the USA is somewhere on the spectrum between these two extremes due to their mix of different electric energy generation assets. Figure 25 through Figure 30 compares how the best performing heating system in each state would perform in that climate when powered entirely by coal, natural gas or renewable sources.

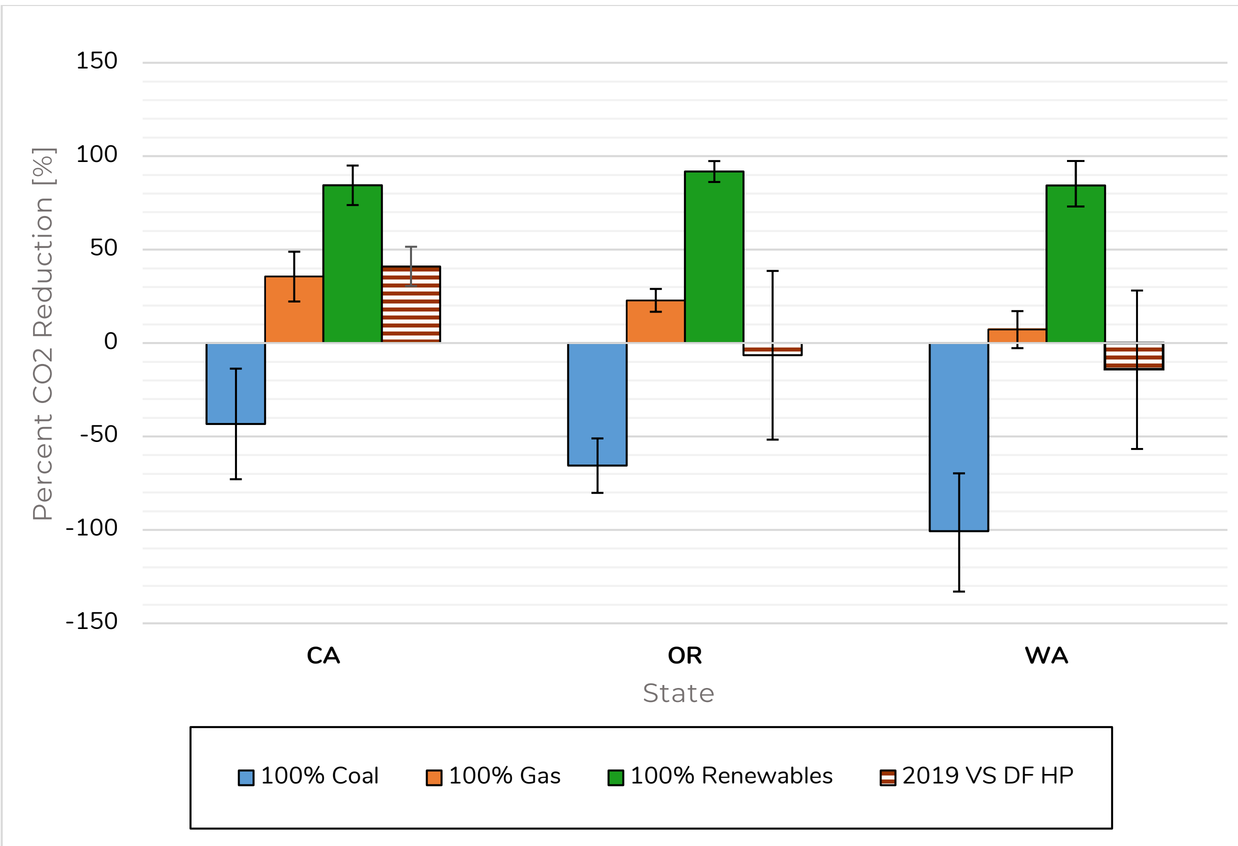


Figure 25 - CO2 reduction under theoretical power generation scenarios in the United States Pacific. Error bars show 1 standard deviation among the cities simulated in that state.

The variable-speed dual-fuel heat pump produced the least annual CO_2 emissions of the 4 heat pumps simulated in all three states of the Pacific region of the USA. California was the only state in the Pacific region where electrification of the heating systems resulted in a reduction in CO_2 emissions. If future investments in renewable power generation assets were to meet the additional electric load from electrifying heating systems, the dual-fuel heating systems would still reduce annual CO_2 emissions by between 84% and 100% when compared to natural gas furnaces in the Pacific region of the USA.

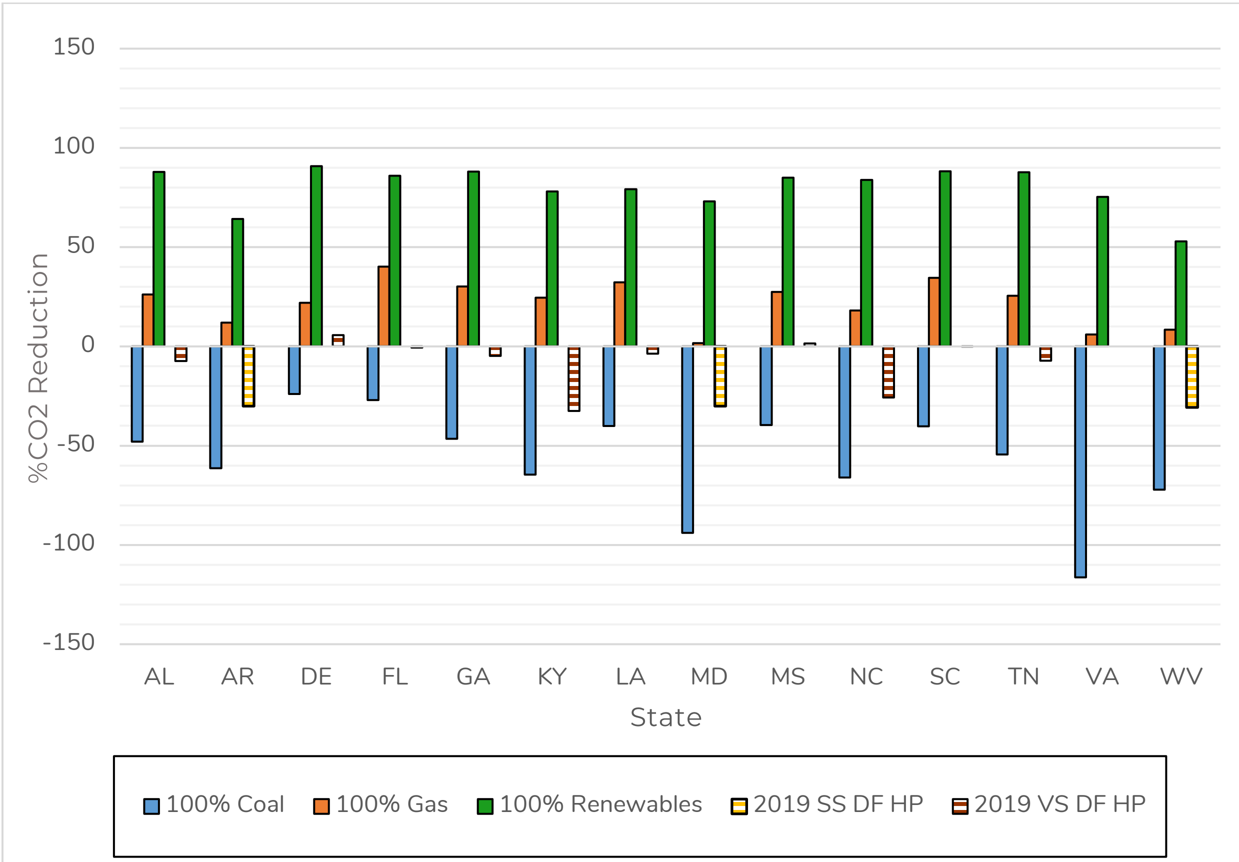


Figure 26: CO_2 reduction in various polarized power conidtions in the United States Souheast.

Of the 14 states in the Southeast region of the USA, the single-speed dual-fuel heat pump produced the least annual CO_2 emissions in 3 of the states and the variable-speed dual-fuel heat pump produced the least annual CO_2 emissions in the remaining 11 states. With current grid conditions, electrification of the heating system increased annual CO_2 emissions in all 14 states. If future investments in renewable power generation assets were to meet the additional electric load from electrifying heating systems, the dual-fuel heating systems would still reduce annual CO_2 emissions by between 54% and 88% when compared to natural gas furnaces in the Southeast region of the USA.

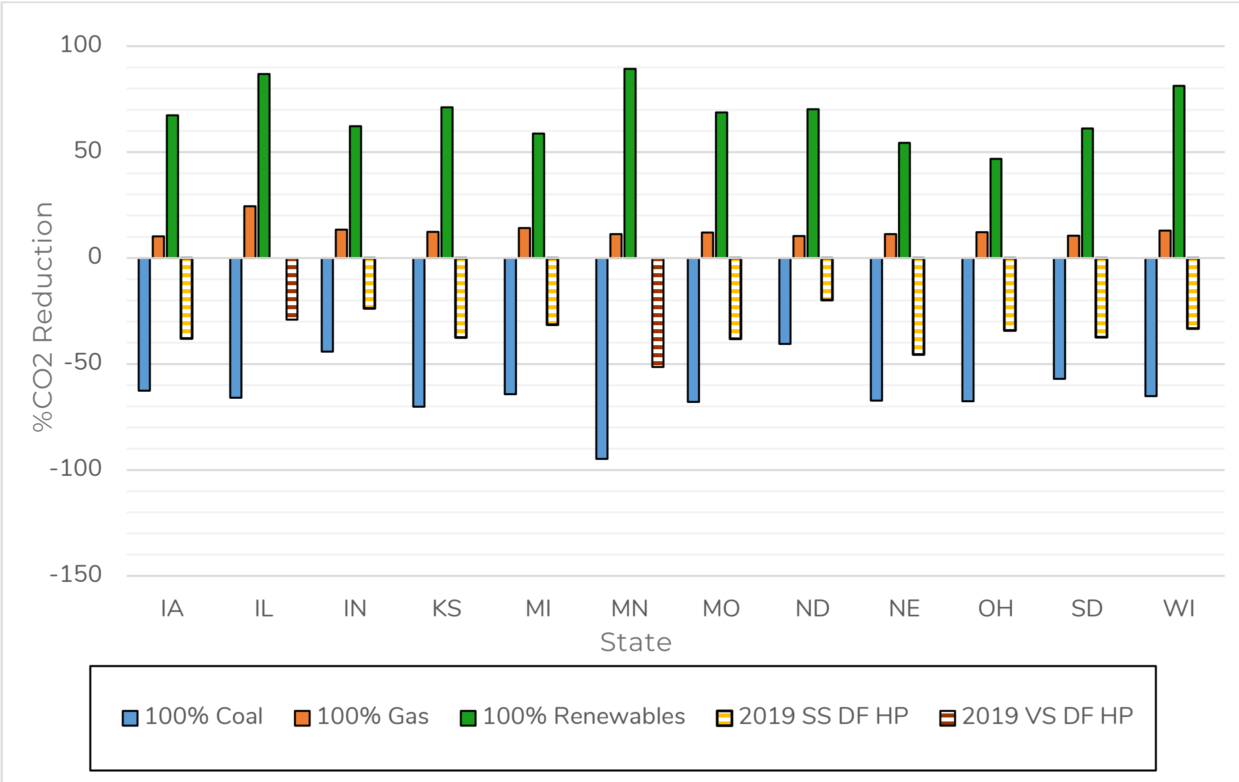


Figure 27: CO_2 reduction in various polarized power conidtions in the United States Midwest.

Of the 12 states in the Midwest region of the USA, the single-speed dual-fuel heat pump produced the least annual CO_2 emissions in 10 of the states and the variable-speed dual-fuel heat pump produced the least annual CO_2 emissions in the remaining 2 states. With current grid conditions, electrification of the heating system increased annual CO_2 emissions in all 12 states. If future investments in renewable power generation assets were to meet the additional electric load from electrifying heating systems, the dual-fuel heating systems would still reduce annual CO_2 emissions by between 46% and 89% when compared to natural gas furnaces in the Midwest region of the USA.

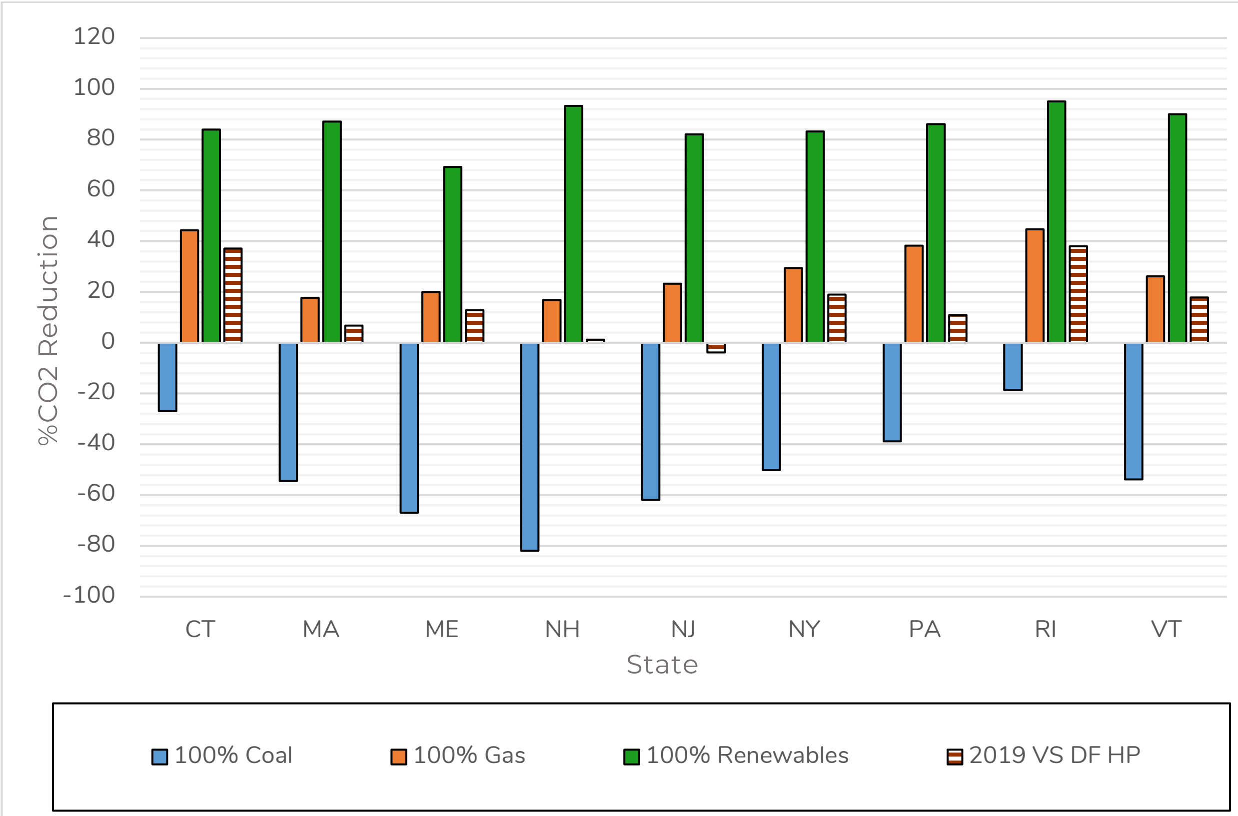


Figure 28: CO_2 reduction in various polarized power conidtions in the United States Northeast.

The variable-speed dual-fuel heat pump produced the least annual CO_2 emissions of the 4 heat pumps simulated in all nine states of the Northeast region of the USA. New Jersey was the only state in the region where electrification of the heating systems resulted in an increase in CO_2 emissions. If future investments in renewable power generation assets were to meet the additional electric load from electrifying heating systems, the dual-fuel heating systems would still reduce annual CO_2 emissions by between 69% and 95% when compared to natural gas furnaces in the Northeast region of the USA.

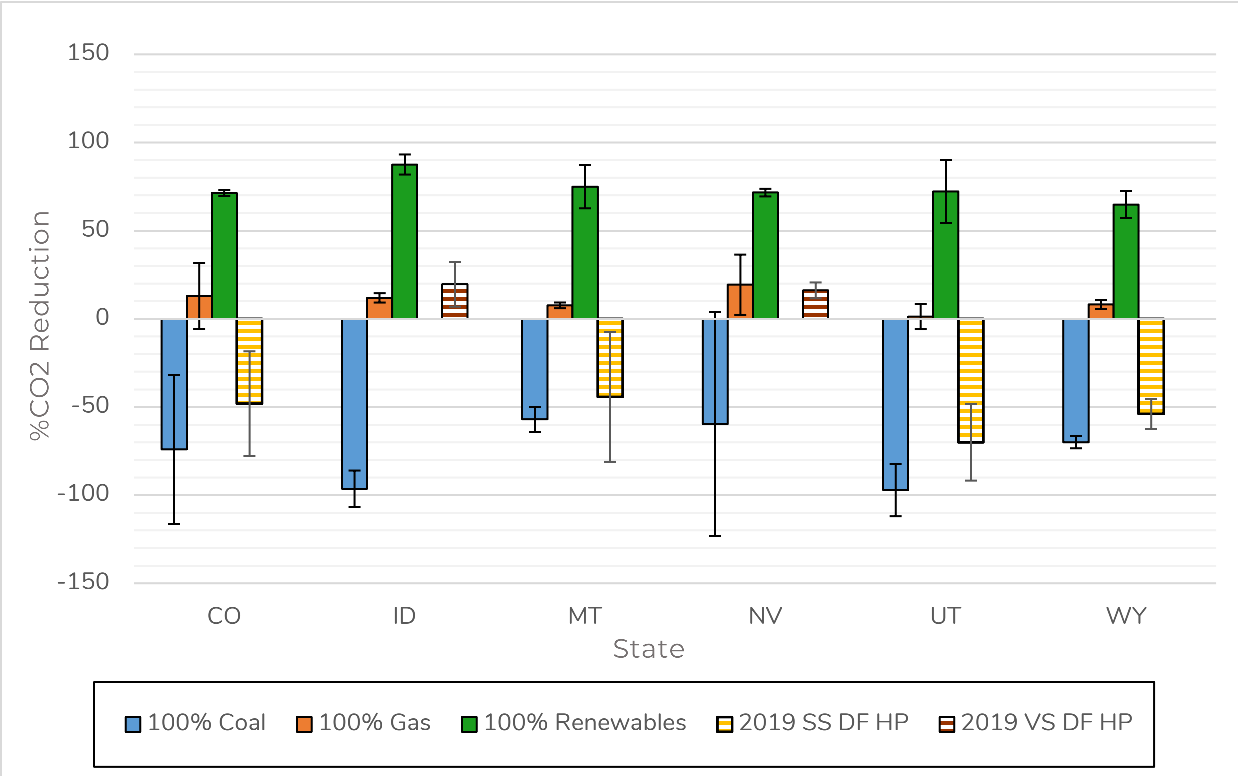


Figure 29: CO_2 reduction in various polarized power conidtions in the United States Rocky Mountains.

Of the 6 states in the Rocky Mountains region of the USA, the single-speed dual-fuel heat pump produced the least annual CO_2 emissions in 4 of the states. The variable-speed dual-fuel heat pump produced the least annual CO_2 emissions in the remaining 2 states, Nevada and Idaho, which were also the only states in the region where electrification of the heating systems resulted in a reduction in CO_2 emissions. If future investments in renewable power generation assets were to meet the additional electric load from electrifying heating systems, the dual-fuel heating systems would still reduce annual CO_2 emissions by between 64% and 87% when compared to natural gas furnaces in the Southeast region of the USA.

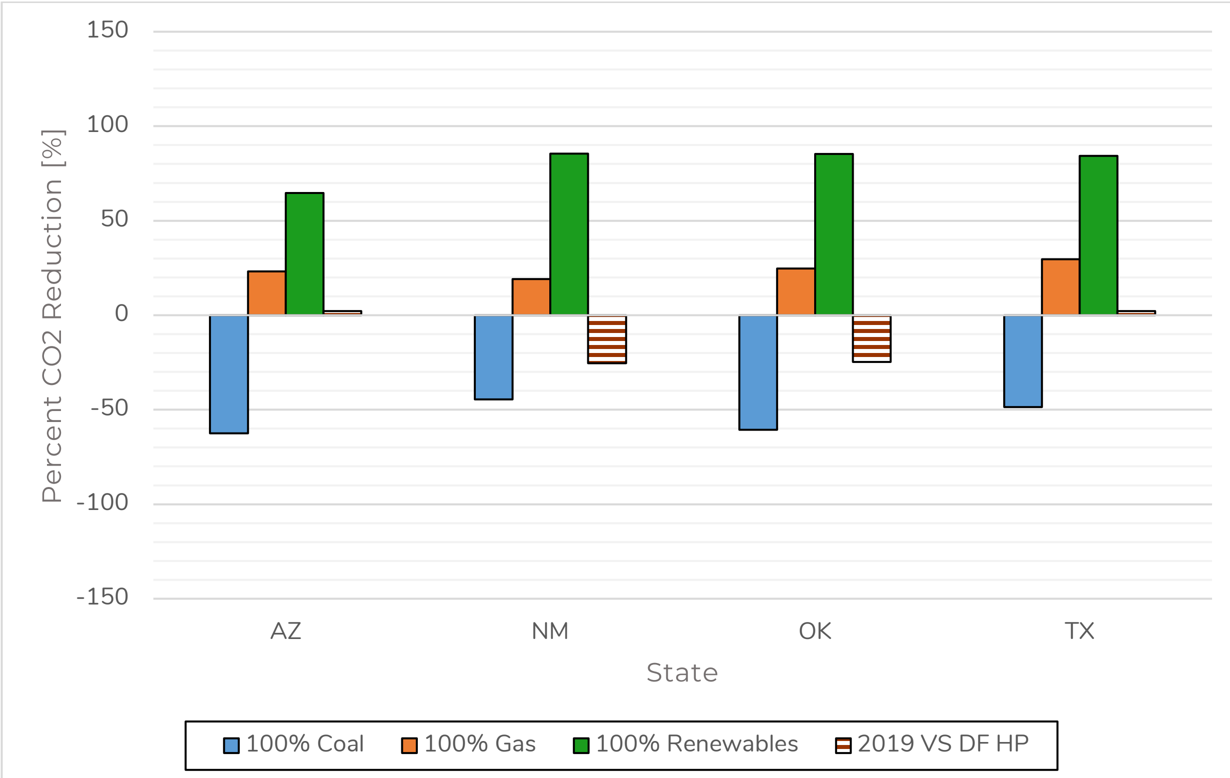


Figure 30: CO_2 reduction in various polarized power conidtions in the United States Southwest.

The variable-speed dual-fuel heat pump produced the least annual CO_2 emissions of the 4 heat pumps simulated in all four states of the Southwest region of the USA. With current grid conditions, electrification of the heating system increased annual CO_2 emissions in New Mexico and Oklahoma and had less than a 3% impact on the annual CO_2 emissions in Texas and Arizona. If future investments in renewable power generation assets were to meet the additional electric load from electrifying heating systems, the dual-fuel heating systems would still reduce annual CO_2 emissions by between 64% and 85% when compared to natural gas furnaces in the Southwest region of the USA.

Figure 31 shows the average percent reduction in annual CO2 emissions of a dual-fuel heat pump powered by 100% renewable sources compared to a natural gas furnace in each region of the USA.

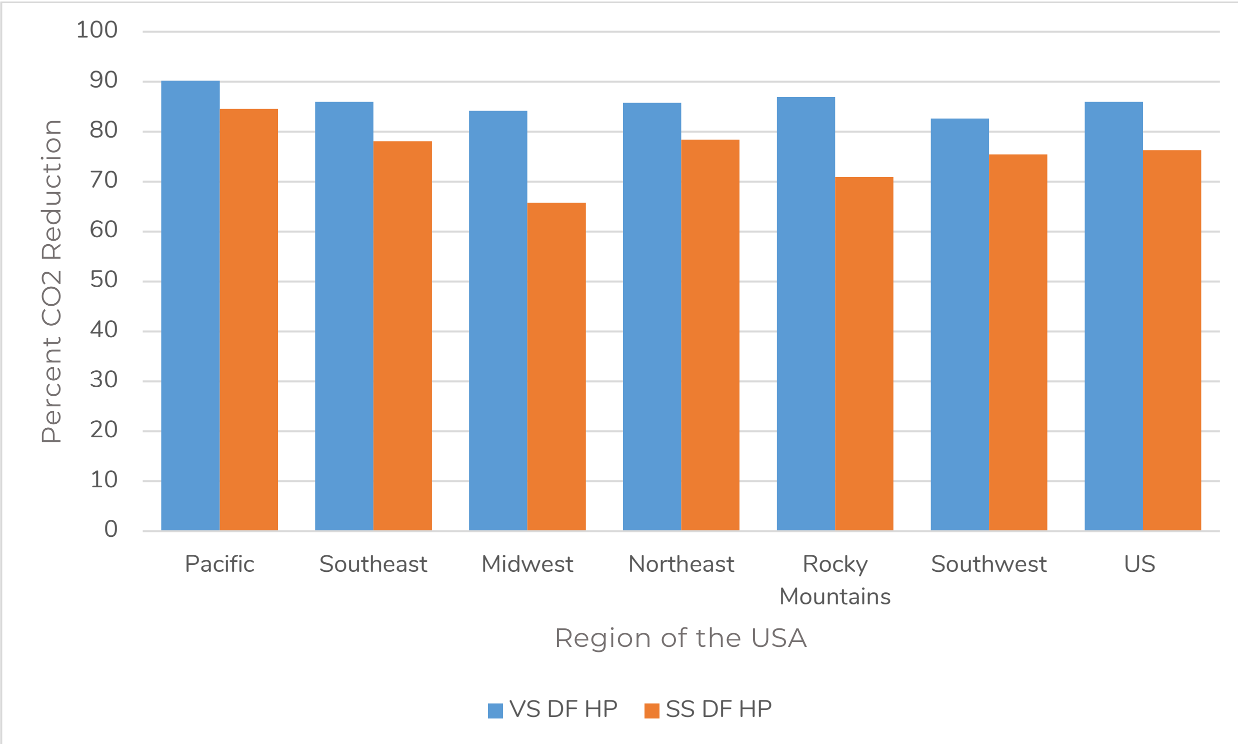


Figure 31 – Percent reduction in annual CO2 emissions of a dual-fuel heat pump powered by renewable sources compared to a natural gas furnace.

A heat pump can have an expected service life of more than 20 years. If electric grids across the USA completely decarbonize in the future, between 65% and 90% of the CO2 emissions reductions that would be achieved by all-electric heat pumps operating on a decarbonized grid would still be realized by dual-fuel heat pumps that are in service after that grid transformation.

CONCLUSION

Complete and partial electrification of residential heating systems through replacing natural gas furnaces with all-electric and dual-fuel heat pumps had a varied impact on GHG emissions in different parts of the USA. With current grid conditions, complete and partial electrification of residential heating systems reduced CO_2 emissions by as much as 41% when compared to natural gas furnaces in 15 states. In the other 33 states simulated, complete and partial electrification of residential heating systems increased CO_2 emissions when compared to natural gas furnaces by as much as 155% when compared to natural gas furnaces.

The heat pump that resulted in the least CO_2 emissions varied between states in the USA. With current grid conditions, dual-fuel systems emitted less CO_2 than their all-electric counterpart in every state and in 37 states, the single-speed dual-fuel heat pump emitted less CO_2 than the variable-speed electric heat pump.

Although an electric heat pump would eliminate CO_2 emissions from heating systems when powered by a renewable source, the current state of the electric grids in the USA have a long way to go to achieve a 100% decarbonized grid. When an electric grid becomes 100% renewable at a future date, dual-fuel heat pumps, which emits less CO_2 than electric heat pumps today, will still reduce annual CO_2 emissions by 76% on average for the single-speed dual-fuel heat pump and by 86% on average for the variable-speed dual-fuel heat pump when compared to a natural gas furnace.

Responsible and effective programs and policies promoting electrification aimed at reducing CO_2 emissions must coincide with investments in renewable electric energy sources otherwise they will at best be ineffective and at worst, a push for electrification absent such infrastructure investments will actually increase annual CO_2 emissions in the majority of the USA. As electric grids are undergoing this transformation to decarbonize electricity, dual-fuel heat pumps can serve as an important bridge technology by emitting less CO_2 today than all-electric heat pumps and still providing the majority of the benefit of an all-electric heat pump in the future as the electric grids move towards decarbonization.

Bibliography

[1] United States Environmental Protection Agency, "Overview of Greenhouse Gases," EIA, [Online]. Available: https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

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

[3] Energy Information Administration, "SHORT-TERM ENERGY OUTLOOK," EIA, 07 07 2020. [Online]. Available: https://www.eia.gov/outlooks/steo/report/.

[4] M. C. Baechler, T. L. Gilbride, P. C. Cole, G. M. Heft and K. Ruiz, "High-Performance Home Technologies: Guide to Determining," *BUILDING AMERICA BEST PRACTICES SERIES*, vol. VOLUME 7.3, 2015.

[5] WattTime, "Grid Emissions Intensity by Electric Grid," WattTime, [Online]. Available: https://www.watttime.org/explorer.

[6] "Today's Outlook," California ISO, [Online]. Available: http://www.caiso.com/TodaysOutlook/Pages/emissions.aspx.

[7] "U.S. Overview," U.S. Energy Information Administration, [Online]. Available: https://www.eia.gov/state/.

[8] K. Silver-Evans, I. L. Azevedo and M. G. Morgan, "Marginal emissions factors for the US electricity system," *Environmental science & technology*, 2013.

[9] D. Callaway, M. Fowlie and G. McCormick, "Location, Location, Location: The Variable Value of Renewable Energy and Demand-Side Efficiency Resources," *Journal of the Association of Enviornmental and Resource Economists*, 2018.

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

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

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

[13] "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.