Decarbonizing with Heat Pumps—Most Do, Some Don't

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Using heat pumps is often encouraged as a way to decarbonize. In colder climates with high electric utility emission rates, however, heat pumps can have higher CO_2 production rates than fossil fuel furnaces. Cold climate heat pumps are being developed that are projected to reduce emissions. Refrigerant circuits are more complex and compressors operate at much higher speeds and compression ratios. Energy performance, equipment service life and CO_2 emissions are uncertain. Comprehensive and independent field-testing programs are necessary to more accurately forecast the effectiveness of these and other heat pump decarbonization strategies.

The U.S. Energy Information Administration (EIA) maintains a database of electrical power plant sulfur dioxide (SO_2), carbon dioxide (CO_2) and nitrous oxides (NO_x) emissions from 2013 through 2022.[1] Information is provided by regions, states and individual plants. CO_2 production is listed by metric tons per megawatt-hour, which are converted to lb/kWh (kg/kWh) for this article. When combined with the heat pump demand (kW) or seasonal energy use (kWh), the heating mode decarbonization capability can be compared to the CO_2 emissions of fossil fuel furnaces and their fan motors.

EIA Data and Emissions at Design Heating Conditions For Two Locations

Table 1 is EIA emissions data for several states and the U.S. total. This information is applied to compare the CO_2 emissions for a design loss of 36,000 Btu/h (10.6 kW) in New York for:

- An air source heat pump (ASHP) with a COP = 2.5
- A ground source heat pump (GSHP) with a COP = 4.0
- A 95% annual fuel utilization efficiency (AFUE) natural gas furnace with a 500 W indoor fan and a 100 W combustion air fan.

The heat pump power demands are:

- ASHP (kW) = 36,000 Btu/h ÷ (2.5 × 3,412 Btu/kWh) = 4.22 kW
- GSHP (kW) = 36,000 Btu/h ÷ (4.0 × 3,412 Btu/kWh) = 2.64 kW

Using the New York 2022 Emission Rate of

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0.54 lb/kWh, CO_2, generation for the heat pumps are:

- CO_2 rate (ASHP) = 0.54 lb/kWh × 4.22 kW = 2.28 lb/h (1.04 kg/h)
- CO_2 rate (GSHP) = 0.54 lb/kWh × 2.64 kW = 1.43 lb/h (0.65 kg/h)

The CO_2 emissions from the furnace fans are likewise calculated

CO_2 rate (fans) = 0.54 lb/kWh × (0.5 + 0.1) kW = 0.32 lb/h (0.15 kg/h)

The contribution of CO_2 emissions for the furnace requires the properties of natural gas and a combustion chemistry refresher. This calculation assumes 100% methane (CH_4), which has a heating value of 23,900 Btu/lb (55,590 kJ/kg). The required mass flow rate for the 95% AFUE furnace is:

mfr (CO_2) = 36,000 Btu/h ÷ (0.95 × 23,900) Btu/lb = 1.59 lb CH_4/h (0.69 kg/h)

Recall from combustion chemistry that:

$CH_4 + O_2 \rightarrow CO_2 + H_2O$

The balanced equation using molecular weights for carbon (12), hydrogen (1) and oxygen (16) is:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$
$$12{+}1{\times}4 + 2{\times}16{\times}2 \rightarrow 12{+}16{\times}2 + 2{\times}1{\times}2{+}16$$
$$16 + 64 \rightarrow 44 + 36$$
$$80 \rightarrow 80$$

The CO_2 to CH_4 mass ratio is: 44 ÷ 16 = 2.75 lb CO_2/lb CH_4.

The CO_2 emission rate for furnace combustion is:

- CO_2 rate (furnace) = 1.59 lb CH_4/h × 2.75 lb CO_2/lb CH_4 = 4.37 lb/h (1.99 kg/h)

The total rate with the fans is:

- CO_2 rate (furnace + fans) = 4.37 + 0.32 = 4.69 lb/h (2.13 kg/h)

The ASHP emission rate is 49% of the furnace rate and the GSHP rate is 30% of the furnace rate.

Repeating this process for Indiana with an emission rate of 1.58 lb/kWh provides different results.

- CO_2 rate (ASHP) = 1.58 lb/kWh × 4.22 kW = 6.67 lb/h (3.03 kg/h)
- CO_2 rate (GSHP) = 1.58 lb/kWh × 2.64 kW = 4.17 lb/h (1.90 kg/h)

The CO_2 from combustion remains the same, and the emissions from the fans are:

- CO_2 rate (furnace fans) = 1.58 lb/kWh × (0.5 + 0.1) kW = 0.95 lb/h (0.43 kg/h)
- CO_2 rate (furnace) = 4.37 + 0.95 = 5.32 lb/h (2.41 kg/h)

The ASHP CO_2 emission rate at design conditions is 15% greater than the furnace rate, and the GSHP rate is 28% lower than the furnace rate.

Similar analyses can be performed for other fossils fuels such as propane and heating oil. The mass ratio of propane is 3.0 lb CO_2/lb C_3H_8, and the heating value is 21,670 Btu/lb (50,400 kJ/kg). Values for heating oil vary, but 3.1 CO_2/lb heating oil and 19,200 Btu/lb (44,660 kJ/kg) are suggested.

Complexity and Uncertainty of Seasonal Energy Performance and Carbon Emissions

Accurate prediction of heat pump and furnace seasonal energy consumption, and therefore CO_2 emissions, is limited by several factors. A primary factor of uncertainty is the quality of heat pump installation, service and maintenance. *Figure 1* shows the results of a National Comfort Institute (NCI) survey that

TABLE 1 Power plant carbon dioxide emission rates for selected states.[1]

YEAR	STATE	CO_2 EMITTED (1000 METRIC TONS)	1000 MWh GENERATED	kg CO_2 MWh	lb CO_2 kWh
2022	Massachusetts	9,098	21,026	433	0.95
2022	Vermont	13	2,184	6	0.01
2022	New York	30,788	125,185	246	0.54
2022	Indiana	70,490	98,055	719	1.58
2022	West Virginia	50,376	56,665	889	1.96
2022	Alabama	52,252	144,789	361	0.79
2022	Texas	213,621	525,563	406	0.89
2022	Colorado	29,739	58,044	512	1.13
2022	California	44,448	203,384	219	0.48
2022	Washington	10,787	116,690	92	0.20
2022	U.S. Total	1,650,367	4,230,672	390	0.86

FIGURE 1 Cooling system performance (CSPr) and equipment performance (CEPr) ratios.[2]

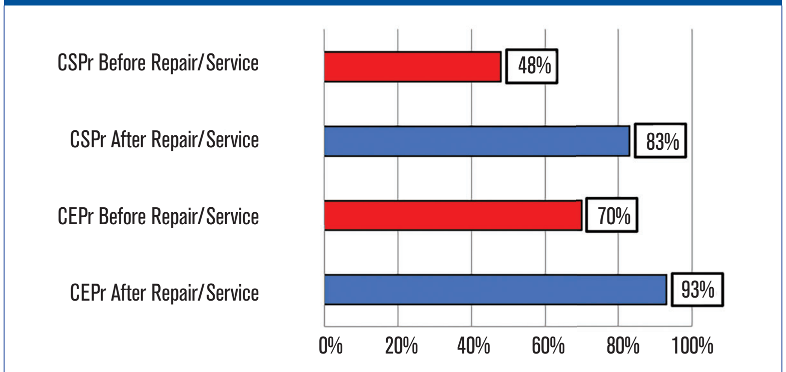
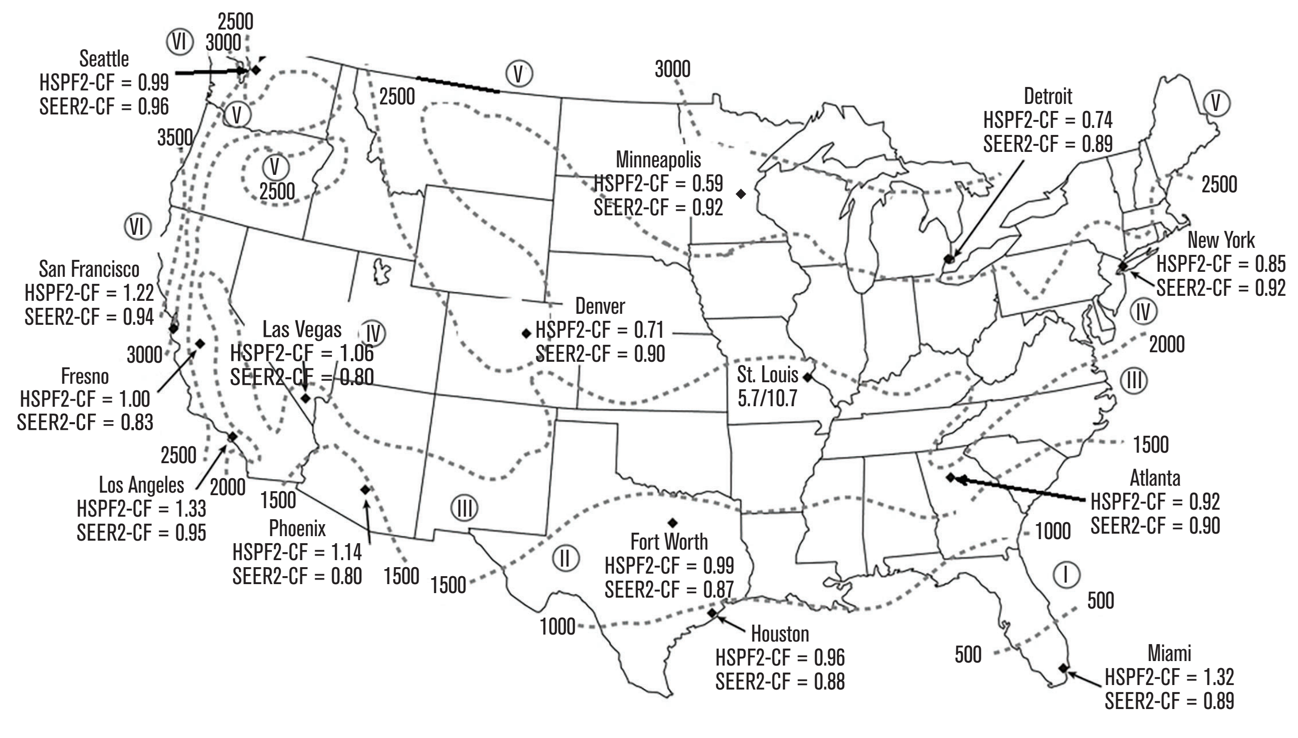


FIGURE 2 Climate-adjusted correction factors for HSPF2 =12/SEER2 = 13 heat pumps.



measured the capacity of 819 cooling units to be only 70% of specified capacity while distribution systems losses resulted in only 48% being delivered to the space. Service performed on 462 of the units increased their cooling capacity to 93% of the specified value with 83% delivered to the space.[2]

The greatest impact on poor equipment performance ratio (CEPr) was enthalpy and temperature change across the cooling coil, often resulting from refrigerant charge issues. This would also affect heat pumps in heating mode. Refrigerant charge is not an issue with fossil fuel furnaces, but no data was presented to substantiate a higher performance ratio compared to heat pumps.

Another limitation for ASHPs performance prediction accuracy is the climate-dependent variation of outdoor coil defrost energy. ASHPs are reversed into the cooling mode to melt frost and snow from the outdoor coil. A cycle typically lasts three to 10 minutes. It can be a timed occurrence (i.e., every 90 minutes) or on demand based on airside outdoor coil pressure drop or temperature difference between the coil and outdoor air.[3] Activation of supplemental (tempering) heat is required to offset the cooling effect and to raise the air delivery temperature to comfortable conditions and avoid "cold blow." Provisions must also be made to ensure adequate drainage of water away from the coil. Operation with the specified level of refrigerant charge, which the NCI study found to be problematic, is important to minimize the frequency and length of defrost operation and tempering heat use.

Estimation of Carbon Emissions Using ASHP HSPF2/SEER2 and GSHP COP/EER

The seasonal ASHP rating of HSPF2 and SEER2 corrected some flaws in the previous bin method energy calculation used to predict HSPF/SEER.[4,5,6]

A study published by the Florida Solar Energy Center (FSEC) analyzed the procedures and assumptions used by the HSPF/SEER rating standard and results of multiple heat pump field tests in several climate zones.[7] A map was created for 14 U.S. locations with corrected HSPF/SEER values for a unit with a 7.8 HSPF and a 12.0 SEER. The ratios of the local HSPF and SEER values to the rated values of 7.8 and 12.0 were used to develop correction factors for HSPF2 and SEER2.

Figure 2 is a modification of the FSEC map to show the correction factors for the 14 locations. Several of the warmer locations had correction factors for HSPF2 greater than 1.0. However, none of the sites had SEER2 correction factors greater than 1.0. This is in part due to the lowering of indoor temperatures in cooling to 78°F (25.6°C) for the study.

Comparative estimates of carbon emissions can be made by applying *Figure 2* correction factors to HSPF2 and SEER2 values. Potential heat pump degradation due to installation and lack of service issues can also be accounted for by applying CEPr values and similar heating equipment performance ratios (HEPr).

GSHP performance is rated at selected entering water temperatures (EWTs) rather than seasonal efficiencies. Heating mode values of capacity (HC) and COP are provided at EWTs of 32°F (0°C), 50°F (10°C) and 68°F (20°C). Cooling performance values of capacity (TC) and EER are provided at 50°F (10°C), 77°F (25°C) and 86°F (30°C). Indoor entering air temperatures are 68°F (20°C) in heating and 80.6°F (27°C) dry bulb/66.2°F (19°C) wet bulb in cooling. Rated COP and EER values only account for the power to distribute air and water though the heat pump but not power required for air and water distribution networks.[8] For unitary heat pump systems with pump power below 7.5 hp/100 tons (15 W_e/kW_t), corrections typically reduce COP values by 15% and EER by 20%.

Properly designed vertical ground heat exchangers (GHEx) provide EWTs to GSHPs 5°F to 15°F (2.8°C to 8.3°C) below local ground temperature (t_g) in heating and 10°F to 25°F (5.6°C to 14°C) above t_g in cooling. Performance corrections are made to the 50°F (10°C) COP rating and the 86°F (30°C) EER rating using average EWTs below t_g for heating and above t_g for cooling. CEPr and HEPr values should be applied to non-optimal designed and maintained GSHP systems.

Table 2 provides the results comparing emissions using a 12 HSPF2/13 SEER2 ASHP, a 4.1 COP/18 EER GSHP and a 95% AFUE/gas furnace with a 13 SEER2 cooling unit. The location is in Denver, which has a 1.13 lb CO_2/kWh state emission rate, 56°F (13.3°C) t_g, and FSEC HSPF2/SEER2 correction factors of 0.71 and 0.90. Values for CEPr and HEPr of 90% were applied to all systems.

Due to the high CO_2 emission rate in Colorado, the ASHP reduces heating emission by only 3% in heating. Cooling emissions are equal to the cooling unit. The GSHP reduces emission 32% in heating and 27% in cooling compared to the furnace/cooling unit. In states with higher CO_2 emission rates, use of ASHPs would be counterproductive, and improvements with GSHPs would be marginal.

Modified Bin Method Energy Calculation Comparison

A third method of comparison is the modified bin method energy calculation that is used to determine HSPF2 and SEER2.[9] It can be adjusted to estimate energy consumption and total annual carbon emissions. A version of this method is applied using local temperature data. Variations to HSPF2/SEER2 procedures include:

- Lowered cooling entering air dry-bulb/wet-bulb temperatures to 75°F and 63°F (24°C17°C), respectively.
- Increased the total ESP to 0.8 in. w.g. (200 Pa) to include typical filter losses.
- Added deductions for defrost energy between 32°F (0°C) and 17°F (-8°C).
- Raised the GSHP heating entering air temperature to 70°F (21°C).
- Applied outdoor air bin temperature values for the example location.
- Adjusted GSHP performance to consider COP/EER reductions as loads increase.
- Included statewide EIA electrical and natural gas costs for the winter of 2023–2024.
- Presented carbon emissions in lb/yr rather than lb/h in previous two comparisons.

Results are shown in *Table 3* for Denver, a city with aggressive emission reduction measures located in a state with high but improving grid emissions. Rated ASHP efficiencies are shown at design conditions rather than HSPF2 and SEER2. Rated GSHP efficiencies at design conditions were reduced to account for demand for fans and pumps due to distribution losses. The carbon emissions for the ASHP are 6% higher than the furnace/AC unit, while the GSHP emissions are 22% lower. Cost of operation is 6% higher for the ASHP than the furnace/AC unit while the GSHP is 19% lower. The program requires the GSHP EER rating 77°F (25°C) EWT rather than 86°F (30°C). The value was raised from 18 in the previous example to 20.

Potential of a Grid to Improve Heat Pump Decarbonization Effectiveness

Projections of significant decarbonization improvements with heat pumps are based on an aggressive addition of low carbon power plants and upgrades to the utility grids. *Figure 3* indicates utilities

TABLE 2 Spreadsheet for estimating Denver emission with ASHP, GSHP and furnace/AC.

Fuel Type	NatGas			Rated HSPF2	12	Btu/Wh
CO_2 Produced Per kWh	1.13	lb/kWh		HSPF-CF From Map	0.71	
Colorado				Air Heat Pump HEPr	90%	
Fuel HHV	23,900	Btu/lb		COP Avg	2.50	
Fuel CO_2 Gen	2.75	lb CO_2/kWh		Rated SEER2	13	Btu/Wh
				SEER-CF From Map	0.9	
Heat Gain	36	kBtu/h		Air Heat Pump CEPr	90%	
Heat Loss	36	kBtu/h		SEERAvg	10.5	
				Air Source Heat Pump		
Furnace AFUE	95%			Input Power-Htg	4.69	kW
Furnace HEPr	90%			Air Ht Pump-CO_2-Htg	5.31	lb/h
Indoor Air Fan Power	500	Watts		Input Power-Clg	3.80	kW
Combust Air Fan Power	100	Watts		Air Ht Pump CO_2-Clg	4.29	lb/h
				Ground Source Heat Pump		
Rated GSHP COP @ 50°F	4.10	W/W		Input Power-Htg	3.33	kW
Rated GSHP EER @ 86°F	18.0	Btu/W·h		GSHP CO_2-Htg	3.76	lb/h
Local Ground Temp	56.0	°F		Input Power-Clg	2.77	kW
Geo Heat Pump SCOP	3.52	W/W		GSHP CO_2-Clg	3.13	lb/h
Geo Heat Pump HEPr	90%			Furnace and Cooling Unit		
Geo Heat Pump SEER	14.4	Btu/W·h		Nat Gas Rate	1.76	lb/h
Geo Heat Pump CEPr	90%			Fan Power	0.60	kW
Cells With This Color Are Input Values				Furnace CO_2-Htg	5.52	lb/h
Cells With This Color are Output-Do Not Change				Air Clg. Unit CO_2-Clg	4.29	lb/h

have made radical changes to the mix of new generating facilities. In 2013 the MW capacity of new natural gas facilities doubled the installation of new wind and solar. In 2020 the new installed capacity of wind and solar generators was almost five times as large as natural gas installations.[10] The dramatic reduction in cost for wind and solar plants provides added incentives for electric utilities. While the wind doesn't always blow and the sun always shine, when they do utilities can avoid significant fossil fuel costs.

In spite of added wind and solar facilities, the figure indicates improvements in grids of states with aggressive heat pump programs have encountered a stagnation or even a slight increase of CO_2 generation per energy output. This is also true of the U.S. grid. A notable exception is Vermont, the state with by far the lowest amount of CO_2/kWh in the U.S. Over half the generation is from hydroelectric power, some of which comes from Canada. However, Vermont has the highest percentage of homes and schools heated by wood and third highest percentage heated by fossil fuels. Vermont does have significant emissions from wood heat and fossil fuels.[11] While legal barriers to interconnect Canadian Hydropower to other states have been somewhat resolved,[12] uncertainties and electrical load growth make CO_2 emission predictions uncertain. States with high CO_2 emission rates relative to electrical energy output like Colorado have made improvements. Future concerns are warranted given the rapid rise of data center consumption and changes in the national commitment to curb emissions.

Conclusions

- In areas with high emission rates of CO_2/kWh, the use of ASHPs is counterproductive to decarbonization efforts, and the benefits of GSHPs are marginal. This is especially true in colder climates.
- The discrepancy between the projected performance of cooling equipment (which are heat pumps) and the actual output is a significant concern for decarbonization efforts with heat pumps that both cool and heat.
- The significant growth of wind and solar generation capacity is encouraging in terms of reduction of both carbon emissions and cost of fuel (fossil and nuclear). However, the minimal improvement of national emission rates of CO_2/kWh is disconcerting.

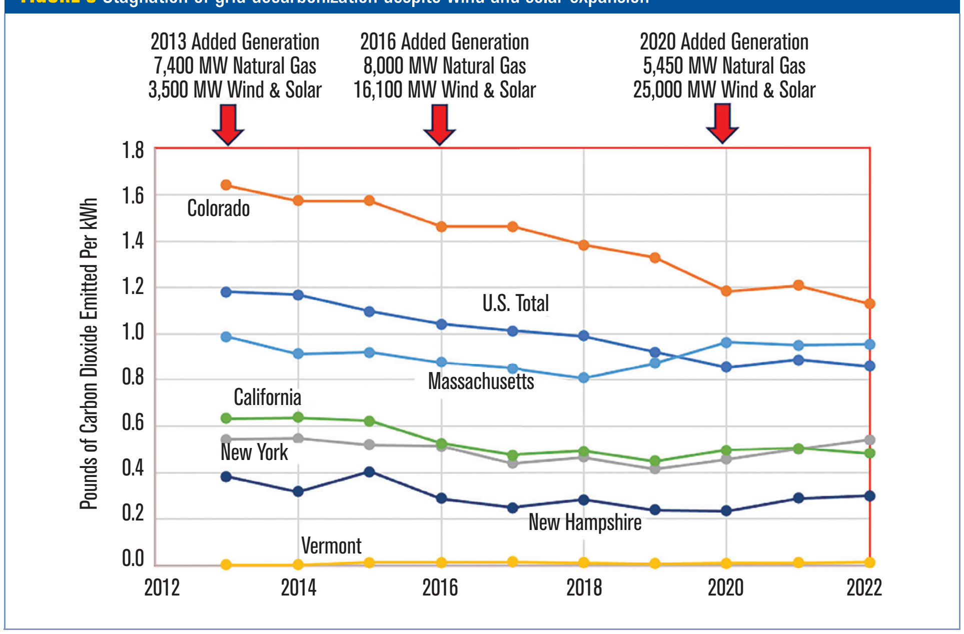
Recommendations

- Heat pump programs and strategies for decarbonization should consider the EIA future (2050) carbon emission estimate.[13]
- Independent and thorough field testing of conventional and advanced technology heat pumps similar to the NCI study should be conducted. This type of effort will better inform decarbonization efforts and minimize deceptive cold climate heat pump performance specifications.[14]
- The EIA also tracks building energy consumption. Data indicate that in spite of increased stringency in building codes and energy standards, the energy use per person increased from 77.1 MBtu/worker (81,300 MJ/worker) in 1992[15] to 79.1 MMBtu/worker (83.455 MJ/worker)

TABLE 3 Comparative Denver carbon emissions using bin temperature method.

Energy Use, Cost and CO_2 Emissions of 12 EER @ 95°F/3.2 COP @ 17°F ASHP							Denver
Cooling $0.118/kWh			Heating $0.118/kWh			CO_2lb/kWh = 1.13	
	Cooling	Heating	Aux Ht.			Defrost Adjustment	
	Occ. & Unoc.	Occ. & Unoc.	Occ.	Unoc.	Total	Dry Climate	
kWh	2,721	8,847	2,720	0	14,288	**CO_2 Emissions (lb/yr)**	
Cost ($/yr)	**$321**	**$1,044**	**$321**	**$0**	**$1,686**	**16,145**	
Energy Use, Cost and CO_2 Emissions of 20 EER @ 77°F/4.1 COP @ 50°F GSHP							Denver
Cooling	$0.118/kWh		Heating	$0.118/kWh		CO_2lb/kWh = 1.13	
	Cooling	Heating	Aux Ht.	Aux Ht.	Pump (oc)	Total	
	Occ. & Unoc.	Occ. & Unoc.	Occ..	Unoc.	H&C		
kWh:	1,337	8,997	299	0	228	10,862	**CO_2 Emissions (lb/yr)**
Cost($/yr)	**$158**	**$1,062**	**$35**	**$0**	**$27**	**$1,282**	**12,274**
Energy Use, Cost and CO_2 Emissions of 12 EER @ 95°F AC Unit/95% AFUE Gas Furnace							Denver
Electrical	$0.118/kWh		Fossil Fuel	$1.149/ccf		CO_2lb/kWh = 1.13	
	kWh Cooling	kWh Heating	Heating Fossil			**CO_2 Emissions (lb/yr)**	
	Occ. & Unoc.	Occ. & Unoc.	Occ. & Unoc.	Total	**Electric**	**3,872**	
kWh	2,449	977	1,029	3,426	**Fossil Fuel**	**11,884**	
Cost($/yr)	**$289**	**$115**	**$1,182**	**$1,586**	**Total**	**15,755**	

FIGURE 3 Stagnation of grid decarbonization despite wind and solar expansion[1,10]



in 2018.[16] These measured values should be considered rather than relying on simulation-based projections alone.

- As evidenced by the NCI study, energy performance and carbon emissions are a strong function of quality installation, design and maintenance. Measured data rating programs, such as the EPA Energy Star Buildings, and HVAC system measurement ratings, such as ANSI/ASHRAE Standard 221, *Test Method to Field-Measure and Score the Cooling and Heating Performance of an Installed Unitary HVAC System,* should be universally applied.

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