Managing the Unintended Consequences of Building Electrification

Rachel Murray, Mahsa Manaei, and Varuna Gopalan, DNV Energy Systems

ABSTRACT

With climate change on the horizon like a *dark* menacing cloud, governing stakeholders are making serious commitments to decarbonization. Heat pumps are viewed as a viable path to decarbonize buildings. Policymakers in states such as Maine, Massachusetts, New York, and California are advocating for aggressively installing heat pumps toward this goal. Program implementers are on board with this plan, but what are the unforeseen outcomes? This paper will discuss results of an analysis performed using ResStock™ building models to investigate the peak demand, energy consumption, energy cost, and carbon impact consequences of residential heat pump electrification in the residential sector.

The paper will use the ResStock analysis to quantify the magnitude of the following questions:

1. How much will emissions be affected by converting to heat pumps in residential buildings previously heated by fossil-fuel heating systems?
2. How much will emissions vary by location?
3. What is the global warming impact of adding refrigerant-based heating systems in homes previously using fossil-fuel heating systems?
4. What is the global warming impact of adding refrigerant systems in homes that did not have central air conditioning pre-electrification?

We will investigate possible solutions to these problems such as targeting those homes where local electricity generation produces low to medium emissions and using heat pumps containing refrigerants that have low global-warming potential. This paper will be useful to policymakers and program implementers who are considering heat pumps as a centerpiece of electrification.

Introduction

In the past five years, dozens of government agencies around the world have developed roadmaps to achieve zero net carbon emissions by 2050. Some have granted these plans the force of law. All of them call for the electrification of fossil-fueled space and water heating equipment in most buildings, using energy-efficient heat pump technology which is available today. Of the nearly 1 million single-family homes built in 2021, 39% had air-source heat pumps (US Census 2022). While heat pumps are installed in approximately 10% of housing units across the US (see Figure 1), in regions with high heating loads, heat pumps are used in only approximately 2% (NREL 2022). This is likely due to older heat pump systems that were less able to meet high heating loads and may have caused persistent reluctance to adopt this technology in very cold regions.

Meeting ambitious carbon reduction goals will require stimulating growth in customer demand for heat pumps as well as strengthening the capacity of the supply chain to promote, manufacture, deliver, install, and maintain them. Utilities, energy efficiency program administrators, regulators, and other policy makers require key information, insights, and solutions to design and deploy effective initiatives to accelerate the installation of heat pumps by their customers and constituents, but with an eye to managing the unintended consequences of such policies.

Technology and Benefits

Rather than burning fuel in the home to make heat—as in a traditional furnace or boiler—a heat pump moves heat from one environment to a refrigerant and then from that refrigerant to a second environment. A heat pump brings heat to conditioned spaces by reversing the vapor-compression cycle used in air conditioning and refrigeration processes—and does so very efficiently. The energy input to a heat pump is used only to compress and move the refrigerant. Thus, heat pumps can achieve efficiencies (defined as the ratio of heat output to electricity input) above 300%. Newer heat pump products are emerging using variable speed fans and variable speed compressors to achieve higher efficiencies in the 400% to 450% range. Given these technical developments, the lifetime cost of ownership for heat pumps has fallen below that of comparable fossil fuel systems in many, but nowhere near all, use cases and market situations.

Recent and ongoing technology advances have expanded the range of applications and conditions in which heat pumps can be used economically. Low-temperature systems enable heat pumps to operate in outside temperatures as low as 5°F. Replacing electric baseboard heating with ductless heat pumps, in which the refrigerant is circulated to fans located within the conditioned spaces without requiring the installation of ductwork, is fifth on the list of single-family home efficiency upgrades yielding the largest contributions to economic potential (NPV[1]>0) for electricity savings (NREL 2017). The application of variable speed compressors and fans, as well as room-by-room temperature controls, deliver enhanced occupant comfort, reduced noise, and increased energy savings.

A recent study that analyzed ResStock data to assess the evolution of the economic benefits and costs of transitioning to heat pumps in homes as their penetration in the US market increases (Deetjen 2021, 1). For this study, 400 representative building models located in 55 US cities were used to simulate the hourly energy use before and after a conversion to a heat pump. The various factors considered and how they might be expected to shift in the coming years are summarized qualitatively in Table 1 where the private monetized benefits and non-benefits are considered in the second and fifth columns. This summary is provided as a means to lay out the many—and sometimes competing—benefits and challenges that heat pumps offer.

[1] Net present value

Table 1. Benefits and consequences of converting from fossil-fuel heating equipment to heat pumps

Category	Benefit	Details	Trend	Non-benefit	Details
Private	Costs, NPV>1	Heat pumps can fully meet the heating load in most US climate zones. Improved heat pump efficacy and efficiency expected.	↑	Costs, NPV<1	In "Cold or Very Cold" climate zone, back-up resistance heating employed that would require grid modifications.
		Home already has central ductwork	-		Central ductwork or mini-split systems needed
		Moderate to good home weatherization	↑		Poor home weatherization
		High cost of fossil fuel compared to electricity, locally	↑		High local cost of electricity
		New heat pump costs	↓		
		Availability of subsidy	↑		
Public, Climate	Reduced CO2e	Low to medium emissions from local electricity generation	↑	Increased CO2e	More emissions from natural gas generators than furnaces/boilers, at premises
		Heat pumps manufacturers reduce use of high-GWP refrigerants[†]	↑		Heat pumps require more refrigerant than AC equipment
Public, Health	Reduced criteria air pollutants	Low to medium emissions from local electricity generation	↑	Increased criteria air pollutants	High emissions from local electricity generation
	Reduced indoor air pollutants[†]	Compared to furnaces/boilers with pilot lights	↓		
	Reduced thermal stress[†]	At homes that previously had no space cooling	–		
	Reduced carbon monoxide poisoning[†]	Elimination of furnace/boiler combustion inside home	–		
	Reduced risk of fire[†]		–		

[†] This factor was not mentioned in Deetjen's 2021 paper; factor was added by authors of this paper.

Space Conditioning Characteristics

NREL's Building Stock Analysis webtool, powered by Tableau®, was used to determine the heating fuels and system types in single-family homes, both detached and attached in the continental United States. The results are shown in Figure 1. With 67 percent of the homes using fossil fuels to produce heat, there is a great deal of opportunity to electrify this end use. The central boiler and furnace systems typically connect to central ductwork systems and could readily be converted to split-system heat pumps. The wall and floor furnace systems could more readily be replaced with ductless heat pumps without incurring the added first cost of duct fabrication and installation.

Figure 1. Proportions of residential heating system and fuel types in continental U.S. *Source:* https://public.tableau.com/shared/YZGHWQPQZ?:display_count=n&:origin=viz_share_link.

The same webtool was again used to determine the proportion of single-family homes with and without central duct systems, and within those categories, those proportions having room AC units, central AC systems, heat pumps, or no cooling. These results are shown in Figure 2. Overall, only seven percent of U.S. homes do not have any air conditioning. If heat pumps are installed in more homes to electrify heating, a fraction of these homes would be expected to begin to use them for cooling, too. Although no study was found to demonstrate the proportion of users that could be expected to use air-conditioning, for the purposes of estimating the effects of this added load on the summer peak during hot days, we assume that all homes with heat pumps will use air conditioning during those times.

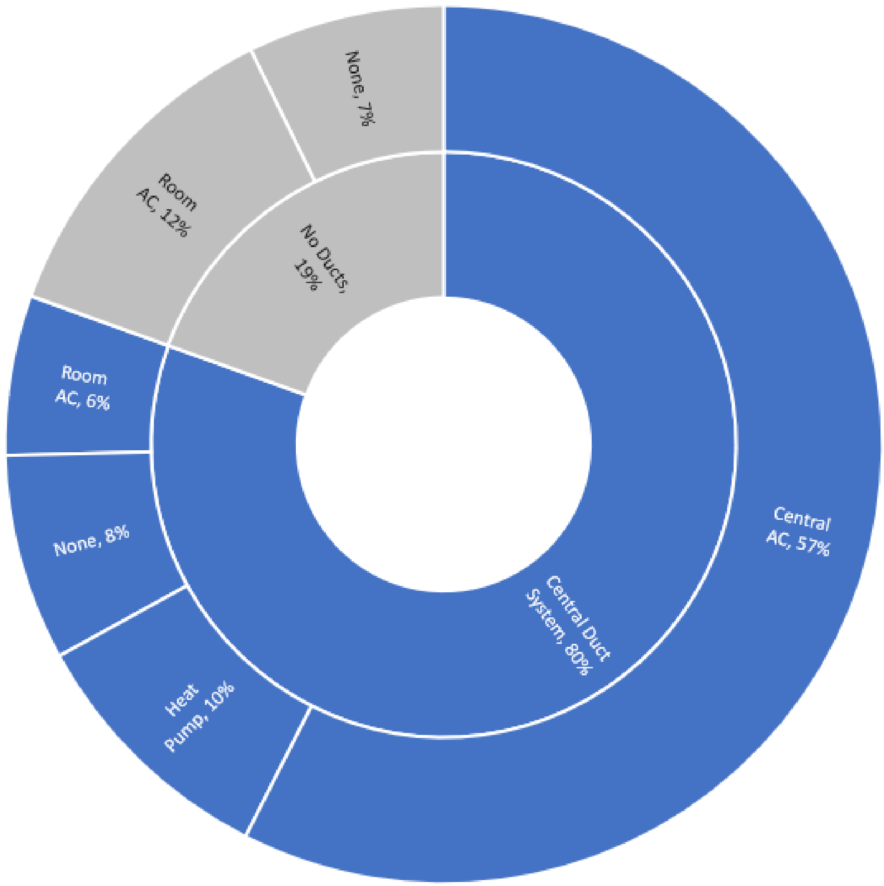


Figure 2. Proportions of single-family homes with and without central duct systems (excluding shared systems) and associated cooling system types in U.S. *Source:* https://public.tableau.com/shared/TJBT26QBX?:display_count=n&:origin=viz_share_link.

Heating Energy Consumption

To estimate the effects of retrofitting existing fossil-fuel heating systems with heat pumps—both ducted and ductless mini-split systems—the Open Energy Data Initiative data lake (OEDI 2022) was used. The data draws from ResStock and combines a mix of building characteristics and EnergyPlus-simulated load shapes gathered from a sample of 377,574 single family homes (detached and attached) across the US. From those homes in the sample, representing the continental US states, 243,183 (64%) were modeled using fossil-fuel heating systems and 35,929 (10%) using heat pumps. This sample is designed to represent the population of single family homes in the continental US as shown in Table 2.

Table 2. Estimated number of single family homes using three types of fossil-fuel heating equipment

Heating System	Estimated Population of Homes Represented (percent)			
	Natural Gas	Fuel Oil	Propane	Combined
Furnace	35,948,708 (61%)	3,330,270 (6%)	3,761,505 (6%)	43,012,637 (73%)
Boiler	6,187,174 (11%)	1,504,844 (3%)	262,229 (0%)	7,968,047 (14%)
Wall/Floor Furnace	6,594,680 (11%)	150,364 (0%)	1,022,519 (2%)	7,775,311 (13%)
Total	48,730,562 (83%)	4,985,478 (8%)	5,046,253 (9%)	58,762,293 (100%)

Source: NREL, 2022. *NREL ResStock Data Viewer*

To determine the heating energy consumption by fossil fuel type, ResStock™ resources were analyzed and are presented in Table 3. ResStock offers a versatile tool that enables large-scale residential energy analysis by combining large data sources, statistical sampling, and detailed building simulations to accurately model the diversity of the single-family housing stock.

Table 3. Annual heating energy consumption of single-family homes by heating system type and fossil fuel using TMY3 weather data

Heating System Type	Annual Heating Energy Usage, MWh (percent)			
	Natural Gas	Fuel Oil	Propane	Combined
Furnace	727,576,117 (55%)	102,492,270 (8%)	80,745,517 (6%)	910,813,904 (69%)
Boiler	143,530,923 (11%)	44,750,906 (3%)	6,228,340 (0%)	194,510,168 (15%)
Wall/Floor Furnace	177,036,668 (13%)	5,100,454 (0%)	28,087,651 (2%)	210,224,773 (16%)
Total	1,048,143,709 (80%)	152,343,629 (12%)	115,061,508 (9%)	1,315,548,846 (100%)

Source: NREL, 2022. *NREL ResStock Data Viewer*

Of the homes in the ResStock sample that use fossil-fuel heating systems—of which 79% have central ductwork—17% do not have any cooling and 21% have one or more room air conditioners. A more detailed breakdown, by fossil fuel is provided in Table 4.

Table 4. Proportions of fossil-fuel heated single family homes that have central ductwork and/or air conditioning

Ductwork	Cooling	ResStock Homes by Heating Fuel, percent		
		Natural Gas	Fuel Oil	Propane
Central	Central AC	52%	5%	6%
	Room AC	6%	1%	1%

Ductwork	Cooling	ResStock Homes by Heating Fuel, percent		
		Natural Gas	Fuel Oil	Propane
	None	8%	1%	1%
None	Room AC	11%	2%	1%
	None	6%	1%	1%

Source: NREL, 2022. *NREL ResStock Data Viewer*

Of the homes in the ResStock sample that use either fossil-fuel heating systems or heat pumps, the average cooling and heating efficiencies are as shown in Table 5.

Table 5. HVAC efficiencies at single family homes with fossil fuel heating systems or heat pumps, weighted averages

ResStock HVAC Equipment	Cooling Efficiency	Heating Efficiency
Heat Pump	SEER 13.2	7.7 HSPF
Central AC	SEER 12.8	-
Room AC	EER 10.5	-
Boiler, Central	-	80.2% AFUE
Furnace, Central	-	82.9% AFUE
Furnace, Wall/Floor	-	65.4% AFUE

Source: NREL, 2022. *NREL ResStock Data Viewer*

Marginal Carbon Dioxide Emissions

Whether it is environmentally beneficial to replace fossil-fuel heating systems with heat pumps is highly dependent upon the regional rate of CO_2 emissions per MWh of electricity generated. To estimate the annual CO_2 emission rates per home for the space conditioning end use, multiple data sources were used to leverage the ResStock simulations results for single family homes with fossil-fuel heating and those with heat pumps at three points in time: 2014, 2024, and 2034.

For equipment assumed to have been installed in 2014, data from multiple sources were combined. The annual per-state CO_2 emissions rates over the span of 2014 to 2020[2] (EIA 2021) were divided by the annual net electricity generation by electric utilities[3] (EIA 2021), to represent the first seven years of HVAC equipment life. There were no data to yet available for 2021, so this year was not accounted for. To represent the final seven years of HVAC equipment life, long-run marginal emission rates (LRMER) for electricity generation were used (NREL 2021) and drawn from the Cambium21 dataset. The long-run marginal emission rate is an estimate of the rate of emissions that would be either induced or avoided by a long-term change in electrical demand. It incorporates both the projected changes to the electric grid as well as the

[2] For Maine, 2019 and 2020 were excluded from levelized rate due to missing annual emissions rates.
[3] For New Jersey, 2014 and 2015 data were excluded from levelized rate due to negative net electric generation.

potential for an incremental change in electrical demand.[4] The Cambium dataset makes it possible to estimate emissions using conservative forecasts of the levelized by-state LRMER over spans of years of interest up to 2050 based on state-level legislation passed as of June 30, 2020.

This effort first utilized the Cambium's "Mid-case" scenario (described as a "business-as-usual" style scenario with moderate technology cost reduction trajectories) as well as the "low renewable energy (RE) costs" scenario for all three installation dates. Using the levelized emissions rates as described, the average per-home annual CO_2 emissions[5] were estimated for the space conditioning end use for those homes with fossil-fuel heating—including the representative mix of homes with central, room/window, or no air conditioning—and for those with heat pumps. These annual emission rates in metric tons are shown in Figure 3 for all states and at the selected installation years. In Figure 4, the upper and lower heat maps show the same data presented in Figure 3, but only for the 2014 installation year.

In Figures 5, 6, and 7, the relative avoided CO_2 emissions are displayed using both the mid-case scenario as well as Cambium's "Low RE Costs"[6] scenario which represents a somewhat more optimistic outlook for reduced emissions from electricity generation in the years to come. Each pair of figures compare the relative avoided CO2 emissions by replacing a fossil-fuel heating system with a heat pump using both forecasting scenarios, in 10-year increments.

The analysis used to generate Figures 3 through 6 assumed a discount rate of 0.04 to inform the levelization weights for each year and considered only direct combustion processes rather than indirect precombustion processes (e.g., fuel extraction, processing, and transport). For the fossil-fuel heating systems modeled by ResStock and shown in the upper heat map in Figure 3, the emission rates used for each of the fossil-fuel heating types were 0.0529, 0.0741, and 0.0613 kg CO_2/kBtuh for natural gas, fuel oil, and propane, respectively. For this effort, the fugitive methane in natural gas was not considered.

Each decade is expected to increase the benefits of electrifying the space conditioning end use in single family homes, but some states will take longer than others. Using either LRMER scenario, however—even without reducing the need for back-up resistance heating via heat pump technology advances and efficiency improvements—is expected to result in dramatic overall emissions reductions within the next 20 years.

[4] The LRMER differ from the more commonly known short-run marginal emission rates which treat grid assets as fixed.
[5] All values use a 100-year horizon.
[6] Renewable energy

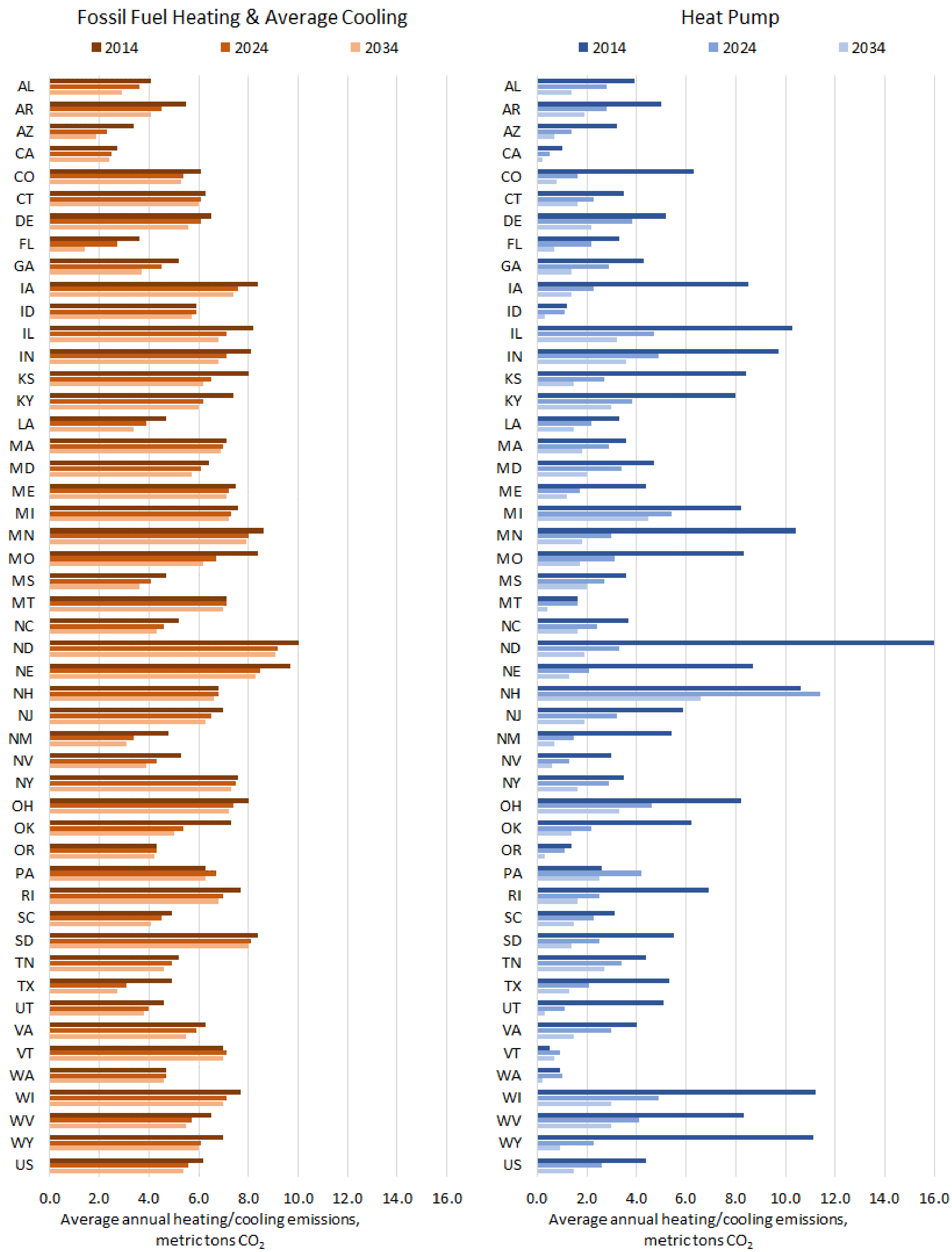
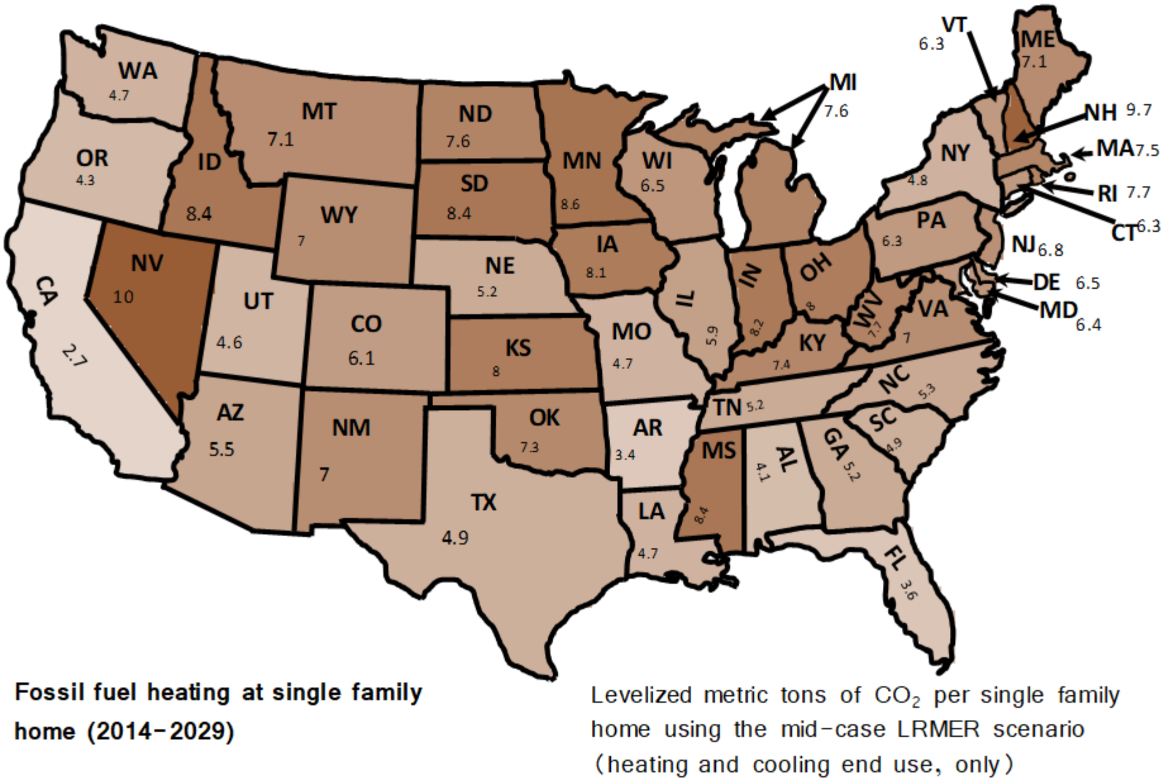


Figure 3. Average annualized metric tons of CO2 by state with fossil fuel heating and average cooling (left) and with heat pump (right) in 2014, 2024, and 2034 assuming 15-year equipment life and using the mid-case forecasting scenario. *Sources:* NREL 2021 Cambium and NREL, 2022. *NREL ResStock Data Viewer*.



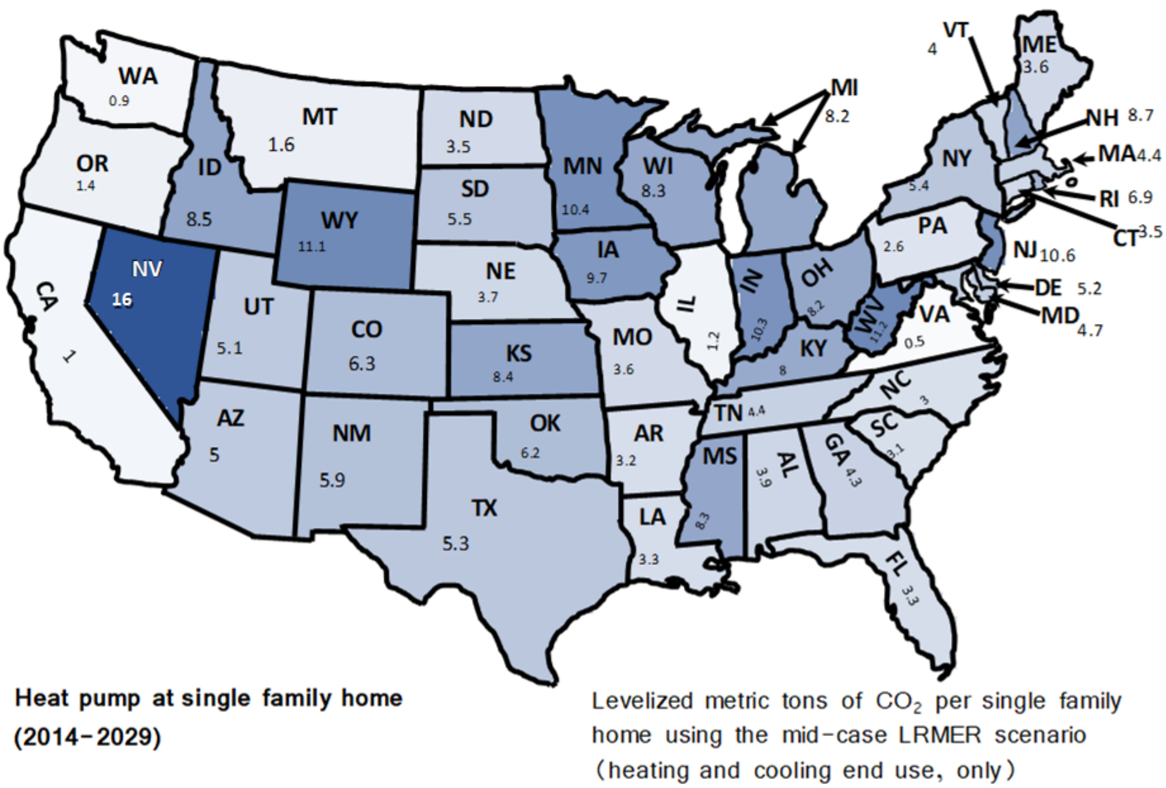
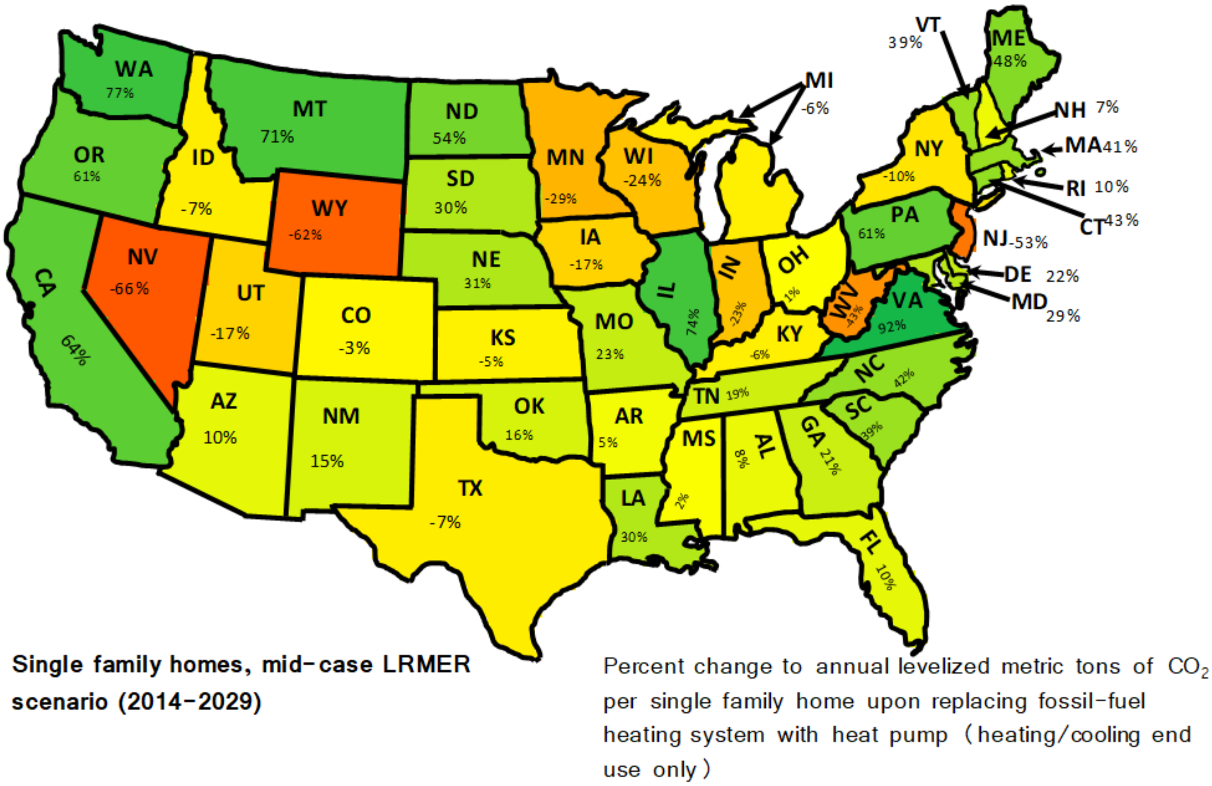


Figure 4. Metric tons of CO2 due to space conditioning end use of a single family home with a fossil-fuel heating system and a representative blend of central, room/window, and no air conditioning (upper map) and with a heat pump system (lower map) using levelized emissions from 2014-2039. *Sources:* EIA 2021, NREL 2021 Cambium, and NREL, 2022. *NREL ResStock Data Viewer*.



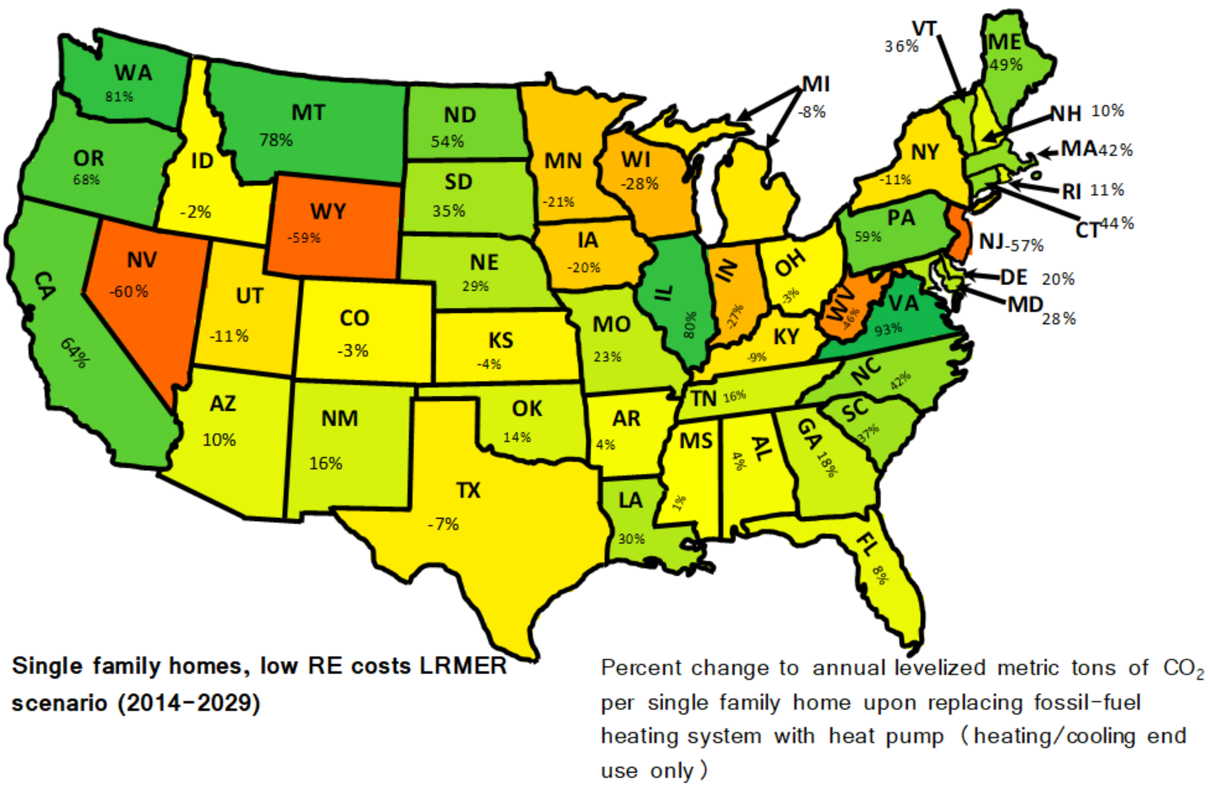
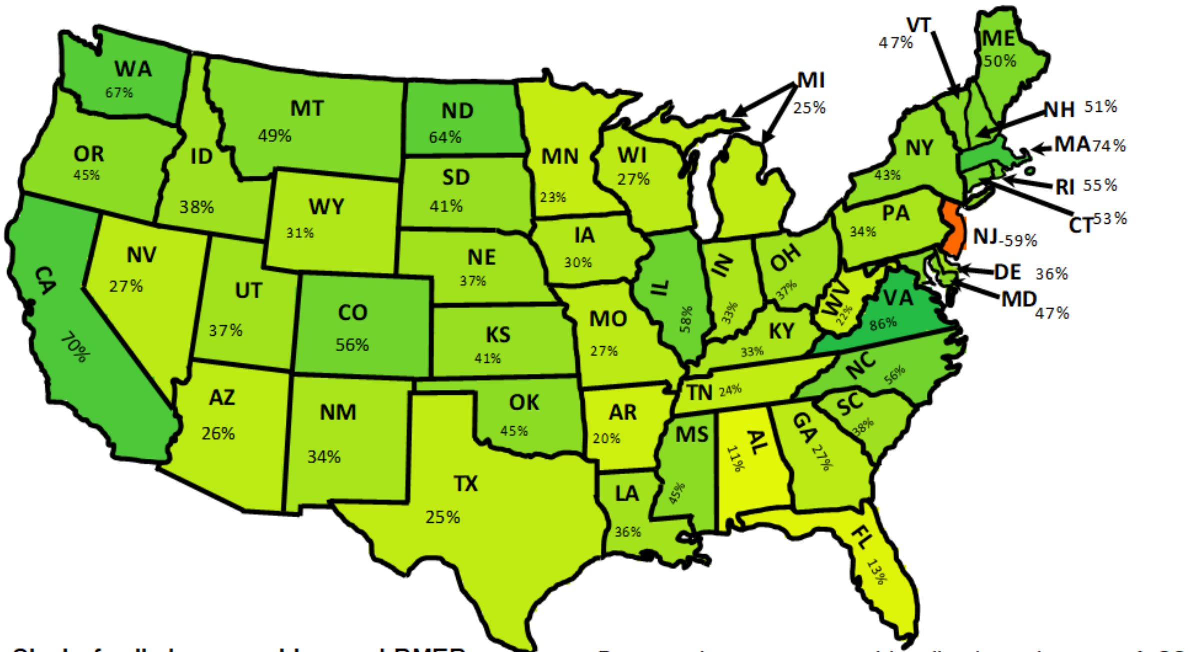
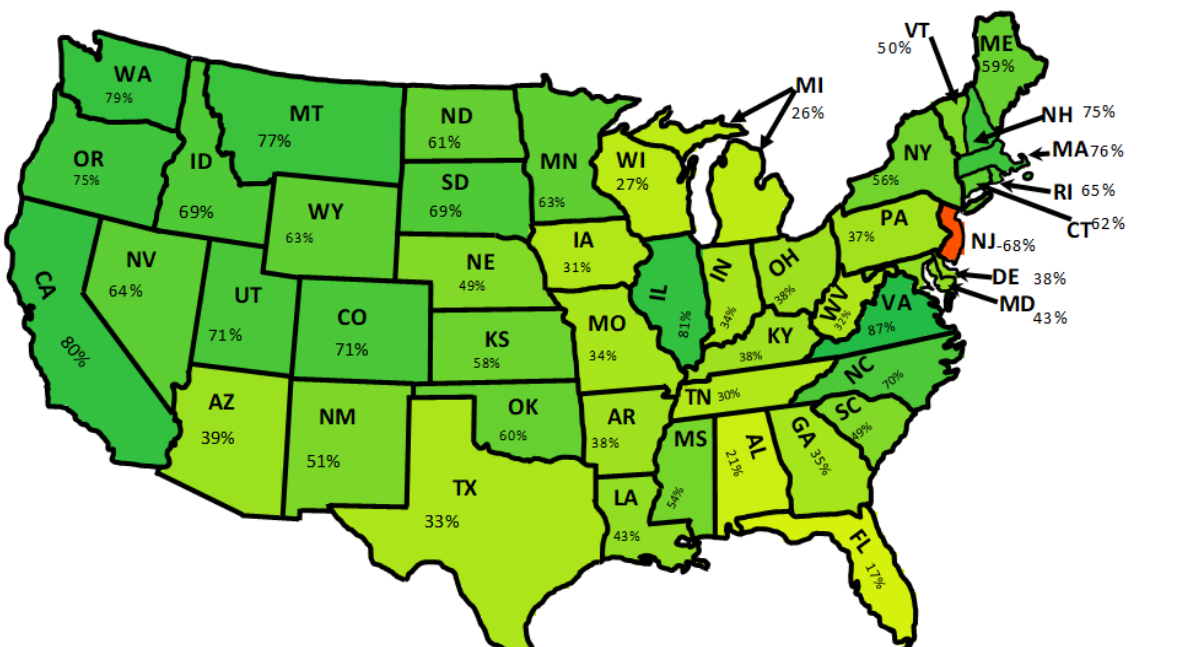


Figure 5. Percent of metric tons of CO2 avoided by state due to replacing a fossil-fuel furnace with heat pump in 2014, assuming 15-year equipment life. *Sources:* NREL 2021 Cambium and NREL, 2022. *NREL ResStock Data Viewer.*



Single family homes, mid-case LRMER scenario (2024-2039)

Percent change to annual levelized metric tons of CO_2 per single family home upon replacing fossil-fuel heating system with heat pump (heating/cooling end use only)



Single family homes, low RE costs LRMER scenario (2024-2039)

Percent change to annual levelized metric tons of CO_2 per single family home upon replacing fossil-fuel heating system with heat pump (heating/cooling end use only)

Figure 6. Percent of metric tons of CO2 avoided by state due to replacing a fossil-fuel furnace with heat pump in 2024, assuming 15-year equipment life. *Sources:* NREL 2021 Cambium and NREL, 2022. *NREL ResStock Data Viewer*.

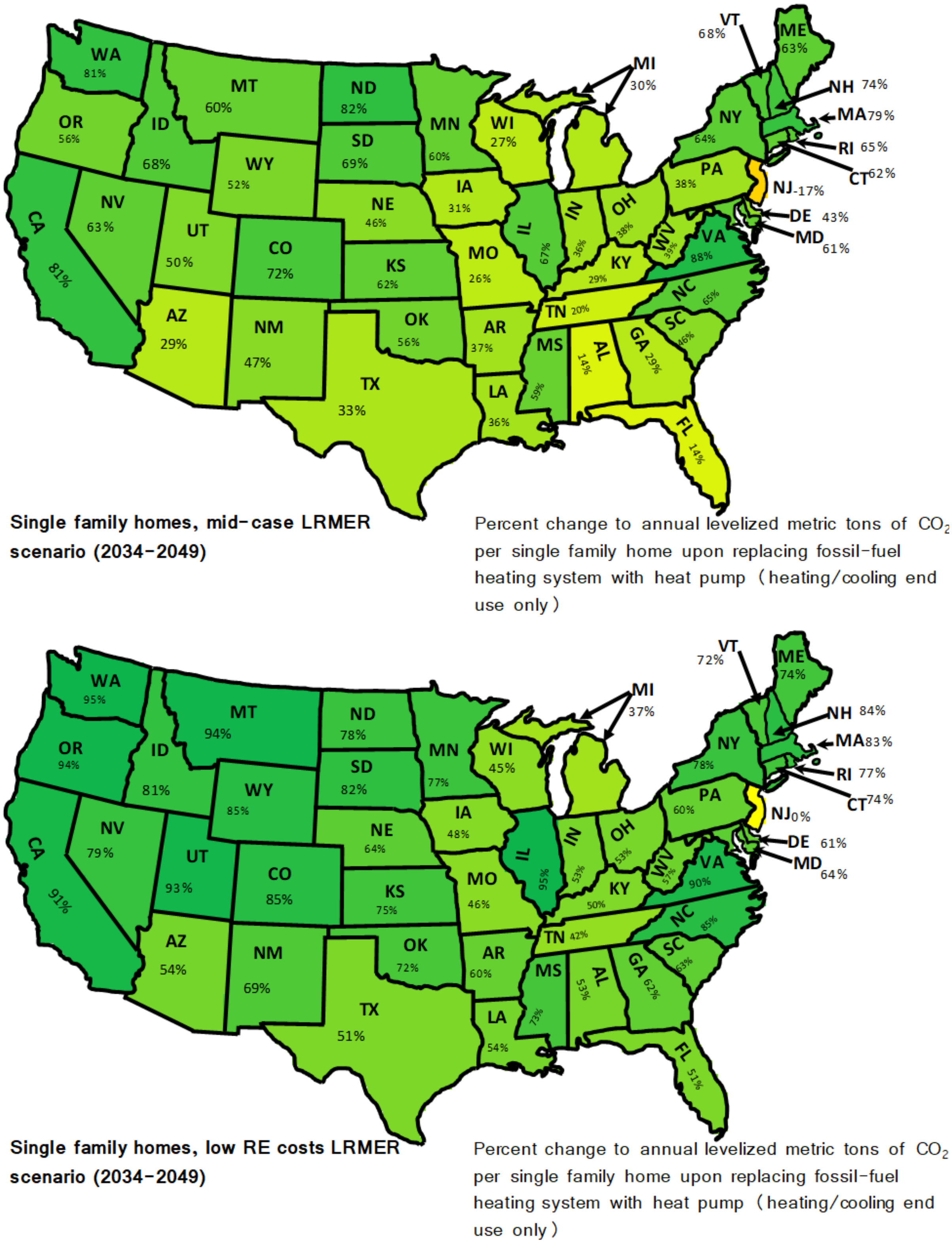


Figure 7. Percent of metric tons of CO2 avoided by state due to replacing a fossil-fuel furnace with heat pump in 2034, assuming 15-year equipment life. *Sources:* NREL 2021 Cambium and NREL, 2022. *NREL ResStock Data Viewer*.

Refrigerant Emissions

One of the adverse effects of converting homes to heat pumps is the global warming potential of the refrigerant contained within the heat pumps and integral to their operation. The results of an analysis, on a per unit basis, are shown in Table 6.

Table 6. Heat pump refrigerant impacts per typical unit

Cooling System Type	Equipment Life, yr.	Average Refrigerant Charge, lb.	Refrigerant Type	Global Warming Potential, metric tons of CO2e		
				Refrigerant GWP[7]	Annual Leakage	End-of-life Leakage
Unitary Heat Pump	15	8.20	R-410A (typ. GWP)	2,088	0.412	5.224
Unitary AC	15	7.50			0.355	4.829
Window/ Room AC	12	1.54			0.029	1.097
Unitary Heat Pump	15	8.20	DR-5 (low GWP)	500	0.099	1.251
Unitary AC	15	7.50			0.085	1.157
Window/ Room AC	12	1.54			0.007	0.263

Source: Beshr et. al. 2016, 8

When the values shown in Table 6 are levelized over the equipment life, as shown in Table 7, and averaged using the proportions of cooling system types presented in Table 4, they can more easily be compared with those values presented in Figures 3 and 4.

Table 6. Annual levelized metric tons of CO2e due to electrification of residential fossil-fuel heating systems

Existing Cooling	New Equipment	Metric tons of CO2e generated due to increased refrigerant		Proportion of Homes
		R-410A, typ. GWP	DR-5, low GWP	
Central AC	Heat Pump	0.07	0.02	62%
Window/Room AC		0.55	0.13	21%
None		0.65	0.16	17%
Weighted average		0.27	0.07	100%

Source: Beshr et. al. 2016, 8 and NREL, 2022. *NREL ResStock Data Viewer*.

When the global warming effects of the increased amount of refrigerant are considered and compared to the CO_2 emissions from the electricity generation required to run the heat pumps, they are relatively small. However, as electricity generation becomes cleaner, the effects of typical refrigerants (with GWP in the thousands) will become more prominent. For the average single family home, emissions drop by 74% with the refrigerant shift shown in this

[7] Global-warming potential

example. For the heat pump installed in 3034—for which the average annualized emissions in the continental US is forecasted to be about 1.5 metric tons CO_2—an accompanying decrease in refrigerant emissions of 0.20 metric tons CO2e can also be realized. It is important that states encourage the use of low GWP refrigerants in lockstep with increasing renewable generation.

Conclusions

While the benefits of electrification are well understood; less understood are the adverse effects of doing so and how those might change over time. Since such a monumental shift cannot take place overnight. It is rational to aggressively target those homes located in regions where the electric power generation produces relatively low emissions first. Further, it makes sense to target those regions where the heating loads of the local climate can be met by existing heat pump technology with a minimum of reliance on back-up resistance heating. Since recent and ongoing technology advances continue to improve the performance of heat pumps in cold climates, these benefits can be added to those forecasted in this paper. Finally, although transitioning from typical refrigerants to those having low-GWP is important, it is dwarfed by the reduced emissions from replacing fossil-fueled heating systems with heat pumps in the right parts of the country. Over time, those regions will eventually encompass the entire US, but this could be accelerated if power generation legislation was adopted nationwide.

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