Cold hard facts: Impact of refrigerant leakage emissions under high residential building electrification

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ABSTRACT

High electrification of fossil-fired heating and water heating with parallel decarbonization of electricity is widely cited as a critical pathway for decarbonizing residential buildings in the United States. Uncertainty remains about a possible drawback from the increased risk of "fugitive" refrigerant leakage emissions as more electric equipment that uses refrigerants is installed in homes across the country. This paper explores the significance of refrigerant emissions leakage to residential building decarbonization in the United States. We integrate data on refrigerant characteristics and leakage rates with a bottom-up model of building technology deployment to characterize the refrigerant leakage emissions of the residential building stock through 2050, under a "business-as-usual" projection and a scenario that assumes high rates of building end-use electrification. In both cases, we compare the magnitude of refrigerant leakage emissions to operational energy emissions and fugitive emissions from leaks in the natural gas supply, and test sensitivities in these estimates. For the high electrification cases, we find that reductions in operational and fugitive methane emissions are substantially larger than increases in refrigerant leakage emissions. Moreover, the significance of added refrigerant emissions is further reduced by the achievement of legislated targets to reduce the consumption and production of hydrofluorocarbons, of which residential equipment refrigerants are a primary source.

Introduction

In the US, residential buildings account for around 20% of US energy-related CO_2 emissions (EIA 2023b). Previous studies highlight that achieving a net-zero economy in the US by mid-century will require high electrification of the buildings sector's fossil-fired heating and water heating end uses alongside parallel decarbonization of the electricity system (Nadel and Ungar 2019; Larson et al. 2020; Kerry and McCarthy 2021; Langevin et al. 2023). This pathway has broad agreement across studies that investigate sector-specific solutions for accelerated decarbonization. However, questions remain about how much accelerated rates of building electrification could increase the magnitude of "fugitive" building emissions from leakage of high-Global Warming Potential (GWP) refrigerants that are used in building air conditioning and refrigeration equipment.

While most existing net-zero pathways studies that include buildings have focused on operational emissions,[1] far fewer investigate the implications of fugitive emissions sources on decarbonization pathways. In addition to refrigerant leakage from building mechanical systems, fugitive building emissions also include methane (CH_4) leakage throughout the natural gas

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[1] Operational emissions refer to onsite combustion of fossil fuels and upstream generation of electricity for building end uses.

supply chain. Building decarbonization requires conversion of building end uses away from gas-consuming equipment to electric alternatives such as heat pumps, which require refrigerants. Electric technologies could therefore have considerable impacts on both sources of fugitive emissions, and improved accounting and characterization of fugitive emissions sources is needed to inform decarbonization strategies and policies.

. Many studies seek to quantify methane emissions across regions of the US as well as across segments of the US oil and natural gas (O&NG) gas supply chain (Alvarez et al. 2018; Omara et al. 2018; Burns and Grubert 2021; Omara et al. 2022; Rutherford et al. 2021).[2] A key metric of these studies is methane emissions intensity of delivered natural gas. Other studies investigate methane emissions from natural gas delivery in buildings (Fischer et al. 2018; Merrin and Francisco 2019; Lebel et al. 2020; 2022). Estimating GHG emissions from leakage of refrigerants from building mechanical systems is also an active research area. This research includes studies of building mechanical systems' leakage rates during their lifetime as well as at end-of-life (EOL) (Gallagher et al. 2014; Hwang 2016; Troch 2016), initial system charge rates (Ashford et al. 2006), and the GWP of existing and emerging refrigerants used in these systems (Ashford et al. 2006; Gallagher et al. 2014; Goetzler et al. 2014).

Fewer studies compare the impacts of the two fugitive emissions sources from buildings – particularly under scenarios with building electrification – and those that do focus on residential buildings. Deetjen et al. (2021) evaluate GHG emissions from methane leakage in an analysis of residential heat pump adoption in representative cities in the US, while Pistochini et al. (2022) consider the comparative impacts of fugitive methane and refrigerant emissions specifically for natural gas furnaces and heat pumps for representative homes across different regions of the US. Similarly, Mahone et al. (2019) evaluate GHG impacts of gas-fired furnaces and heat pumps for representative homes across California.

While these studies present useful insights about fugitive emissions impacts from buildings, important research gaps remain. First, previous studies that consider fugitive emissions sources often do so at the individual scale or for representative building types in specific regions, rather than for the whole buildings sector. Second, existing studies examine fugitive emissions sources under fixed assumptions about heat pump adoption that do not incorporate realistic projections of equipment stock turnover and rates of switching from fossil-fired to electric equipment, which are important in determining the timing with which changes in fugitive emissions sources could occur.

This paper aims to fill these research gaps by presenting an assessment of fugitive emissions from U.S. residential buildings at the national scale, under both reference case conditions and high electrification of home space and water heating equipment to heat pumps. We focus on residential buildings given their high potential for electrification and high expected contributions to overall building decarbonization potential (Langevin et al. 2023). Our study uses a detailed, bottom-up modeling framework to quantify fugitive emissions through 2050, and we compare the scale of additional refrigerant emissions under high electrification to that of concurrent reductions in fugitive methane emissions and in operational energy emissions. We also determine the sensitivity of our estimates to assumed rates of methane leakage and policies related to refrigerant phase-outs. We consider how results for refrigerants may compare with targets in the recently enacted American Innovation and Manufacturing (AIM) Act, which authorizes the EPA to phase down the use of hydrofluorocarbons (HFCs) in air conditioning, refrigeration, and other applications (EPA 2021). Our findings provide a more complete

[2] The full O&NG supply chain includes production, transmission and storage, and local distribution.

accounting of residential building emissions that can inform policies about electrification as a strategy for building decarbonization.

Methods

We produce estimates of buildings sector GHG emissions inclusive of operational emissions and fugitive emissions from equipment refrigerant leakage and natural gas supply chain methane leakage. Figure 1 summarizes the steps in the analysis workflow, which is conducted using a modified version of the Scout software (scout.energy.gov).[3]

The workflow begins with Scout's baseline projections of residential building and technology stock turnover, energy demand, and operational CO2 emissions from 2024-2050. Next, additional data are integrated to estimate fugitive emissions from 1) leakage of residential building equipment refrigerants and 2) methane leaks in the natural gas supplied to meet residential building end-use demand. With these data integrated, upper and lower-bound projections of fugitive refrigerant and methane emissions from 2024-2050 are developed, for both the baseline case and a high equipment electrification case. Finally, the sizes of the projected fugitive and operational emissions sources are compared.

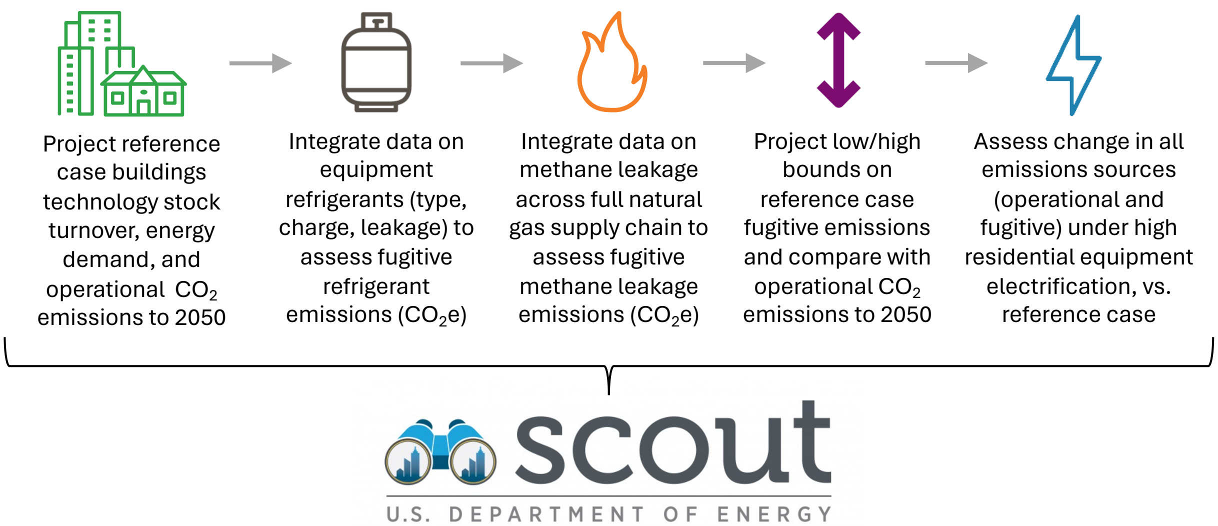

Figure 1. Overview of modeling workflow.

Table 1 summarizes key dimensions of the baseline and high equipment electrification cases that were modeled for this analysis. The following subsections provide further methodological details for the steps in Figure 1 and the scenarios summarized in Table 1.

[3] The Scout codebase is publicly available on GitHub (https://github.com/trynthink/scout). Interested readers can contact the authors for guidance on accessing the supporting code base.

Table 1. Summary of modeling scenarios and key dimensions.

Scenario	**Residential demand**	**Grid emissions** [1]	**Refrigerant GWP**	**Methane leakage rates** [2]
Baseline residential demand and grid, *worst-case* fugitive emissions	AEO 2023 Reference Case (EIA, 2023a)	Cambium 'Mid-Case (with tax credit phaseout)" scenario (Gagnon, Cowiestoll, and Schwarz 2023)	Typical 2020 refrigerants carried forward through 2050	Upper bound (Burns and Grubert (2021))
Baseline residential demand and grid, *best-case* fugitive emissions			Low GWP refrigerants phased into the market starting in 2024	Lower bound
High residential electrification, *least favorable* for refrigerant emissions	Aggressive decarbonization benchmark w/ high electrification (Langevin et al, 2023)	AEO 2023 Reference Case	Typical 2020 refrigerants carried forward through 2050	Lower bound
High residential electrification, *most favorable* for refrigerant emissions		Cambium 'Mid-case with 100% Decarbonization by 2035" scenario	Low GWP refrigerants phased into the market starting in 2024	Upper bound

[1] Less/more aggressive grid decarbonization results in less/more potential offset of added refrigerant emissions from electrification from shifting fossil-based operational emissions to operational electricity emissions.
[2] Lower/upper bounds on methane leakage provide less/more potential offset of added refrigerant emissions from electrification from reductions in methane leakage emissions.

Building modeling framework

We use Scout, a hybrid, Q1/Q4 building stock energy modeling framework to project future US building energy use and operational CO_2 emissions based on stock turnover and the adoption of new building technologies or operational approaches (Langevin et al 2020).[4] We provide an overview of Scout's building stock turnover, energy use projection, and technology adoption components, which facilitate the analysis presented in this paper. Simulations are conducted using a modified version of Scout v0.9.1 that supports sensitivity analysis for fugitive emissions inputs (BTO 2023).

Scout uses a bottom-up model to aggregate specific segments of the US building technology stock, represent stock turnover rates, and make projections of annual buildings sector energy use between 2024–2050. Reference case estimates of technology stock evolution, unit energy consumption (UEC), and CO_2 emissions per unit fossil-based energy consumption are from the 2023 EIA Annual Energy Outlook (AEO) Reference Case (EIA 2023a). CO_2 emissions per unit electricity-based energy consumption are from either the 2023 EIA AEO Reference Case or the Cambium data set developed by the National Renewable Energy Laboratory (Gagnon, Cowiestoll, and Schwarz 2023), depending on the scenario (see Figure 2). Projections in this analysis are aggregated nationally but Scout models impacts with higher regional resolutions and

[4] Scout has been used in previous analyses of the energy, CO_2 emissions, and operating cost impacts of efficient, low-carbon technology adoption in the buildings sector (Langevin et al. 2023; 2021; Langevin, Harris, and Reyna 2019; Satre-Meloy and Langevin 2019). Further details on Scout's methodology are available in the Methods and Supplementary Information sections of those studies.

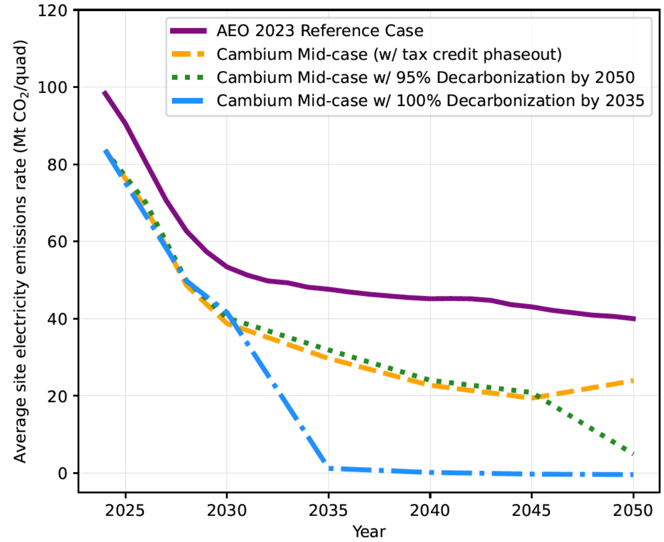

Figure 2. Scenarios of building site electricity emissions intensities used in Scout, based on EIA AEO 2023 (EIA 2023a) and Cambium (Gagnon, Cowiestoll, and Schwarz 2023).

resolves input data by the building types, fuel types, end uses, and technology types used in the National Energy Modeling System (NEMS) (EIA 2020b; 2020a).

Building measure sets and adoption assumptions

Scout models changes in reference case energy use and energy-related CO_2 emissions for various scenarios of building technology or operational measure adoption. Adoption impacts are assessed from the bottom-up for individual building measures. An example is the replacement of existing equipment (e.g., a natural gas furnace) with more efficient alternatives, including technologies that switch fuels (e.g., to electricity). Each building measure is applied to segments of the reference case building stock during the years that the measure is available to consumers. Measure penetration into the baseline stock is based on the rate at which new stock is added or existing stock is replaced. The former follows from AEO projections of new construction and the latter is determined based on existing equipment lifetimes. Measure adoption is also constrained by competition with other measures in the analysis that could satisfy the same energy service. This allows individual measure impacts to be aggregated across a full portfolio without double counting. Alternate scenario estimates of energy use, CO_2 emissions, and equipment and energy costs reflect the effects of the measure portfolio's deployment, and these can be directly compared against reference case estimates.

This paper's reference case for building technology availability and adoption is consistent with Scout's baseline and the AEO 2023 Reference Case. Historical patterns of building technology adoption are extended forward. Though AEO 2023 does represent heat pump incentives from the Inflation Reduction Act legislation, projected fuel switching from fossil-based to electric equipment is minimal. The reference case therefore serves as a "business-as-usual" baseline for fugitive emissions, relative to which the impacts of high electrification can be explored. For electricity emissions intensities, the reference case uses data from the "Cambium Mid-case (with tax credit phaseout)" scenario shown in Figure 2.

The high residential electrification case uses demand-side assumptions from the aggressive building decarbonization benchmark scenario in Langevin et al. (2023). This scenario includes the most aggressive level of residential electrification considered in that analysis, which reflects a combination of favorable technology innovations such as affordable cold climate heat pumps; large federal and utility incentives for electrification to heat pumps; and widespread adoption of codes and standards that are favorable for electrification at the state and local levels. This scenario represents full conversion of fossil-fired heating and water heating equipment to air source heat pumps and heat pump water heaters, as well as aggressive switching of electric resistance-based equipment to heat pumps. Such assumptions result in 2050 heat pump sales shares of 90% and 85% for residential heating and water heating, respectively.[5] We pair these demand-side assumptions with two sets of electricity emissions intensities from Figure 2. In the least favorable case, we use grid emissions factors from the AEO Reference Case (EIA, 2023), which represents slower grid decarbonization. In the most favorable case, we use grid emissions factors from the Cambium "Mid-case with 100% Decarbonization by 2035" (Gagnon et al., 2023) scenario, which represents accelerated grid decarbonization.

The reference case and high electrification scenarios described above generate projections of building equipment stocks, energy use, and operational energy emissions from 2024-2050. Additional assumptions about equipment refrigerants and upstream methane leakage are layered on top of these projections as described in the following section.

Fugitive emissions data and methods

Building equipment refrigerants. To assess CO_2e emissions from refrigerant leakage over the lifetimes of both heat pump (HP) and air conditioning (AC) technologies, we use a modified version of the *total equivalent warming impact* (TEWI) equation (Park et al. 2019) to calculate the direct emissions from refrigerant leakage and end-of-life recovery losses, as in:

$$1)\quad TEWI = (GWP \times m \times L_{annual} \times n) + (GWP \times m \times EOL))$$

where:

- GWP = global warming potential of refrigerant, relative to CO_2 (GWP = 1);
- L_{annual} = leakage rate per year (%);
- n = system operating life (years);
- m = refrigerant charge (kg); and
- EOL = end-of-life emissions as a percentage of initial refrigerant charge (%)

For each technology type modeled in Scout, data are collected from existing sources on typical refrigerants, refrigerant charges, and end-of-life refrigerant leakage (Ashford et al. 2006; Gallagher et al. 2014), typical refrigerant leakage rates (Hwang 2016; Troch 2016), and system operating lifetimes. GWP–100 values from the IPCC Fourth Assessment Report are used to convert refrigerant emissions to CO_2e (Forster et al. 2007). In our analysis, we represent current regulation that affects the use of a given refrigerant (e.g., the U.S. EPA's Final Rule 21 (EPA 2016) prohibits the use of R-410a for chillers as of January 1, 2024). We represent this regulation via a phase-out year after which the conventional refrigerant is substituted with a low-GWP alternative. However, our low-GWP assumptions do not currently reflect requirements in the

[5] The reader is referred to Langevin et al. (2023) for more details about adoption assumptions for the high electrification case.

2021 AIM Act for a phase down of HFC refrigerant production and consumption (production plus inputs minus exports). The AIM Act requires reductions of 85% from an average of 2011-2013 HFC production and consumption levels by 2036 (EPA 2021).

Table 2 shows the input data used for each Scout technology type included in our analysis (EOL refrigerant leakage for all equipment types is assumed to be 15% (Hwang 2016)). Values from equation (1) are assumed for individual technology units in the same manner that per-unit operation-phase CO_2 emissions are assumed.

Table 2. Summary of data used to calculate fugitive emissions from refrigerant leakage.

Equipment	L_{annual} (%)	n (yr)	m (kg)	Typical refrigerant	GWP-100	Low-GWP refrigerant	GWP-100
Room AC	2	18	0.7	R-410A	2088	R-32	675
Air-source HP	5.8	15.5	3.59				
Ground-source HP	5.8	15.5	3.59				
Central AC	5.8	18	2.95				
HPWH	2	13	4.7	R-134A	1430	R-1234yF	<1

Supply chain methane leakage. CO_2e emissions from methane leakage from oil and natural gas supply are based on leakage rates across various segments of the natural gas industry to calculate methane leakage rate factors for consumption of natural gas. These factors are used to calculate fugitive methane emissions from baseline building sector natural gas consumption as well as avoided methane emissions when fuel switching to electricity.

Previous assessments of emissions from methane leakage in oil and natural gas supply find that the U.S. EPA's Greenhouse Gas Inventory (GHGI) has underestimated leakage. Alvarez et al. (Alvarez et al. 2018) find in a recent bottom-up assessment of methane emissions across the oil and natural gas industry segments that emissions are underestimated for production. We incorporate data on methane leakage rates at the state-level using recent work from Burns and Grubert (2021). Their study uses basin-level estimates of production-stage methane emissions in combination with data on natural gas production, consumption, and trade to attribute production-stage methane emissions to individual states. Figure 3 shows the state-level leakage rates from Burns and Grubert, and Table 3 shows estimates of average leakage rates for the other oil and natural gas segments from Alvarez et al.

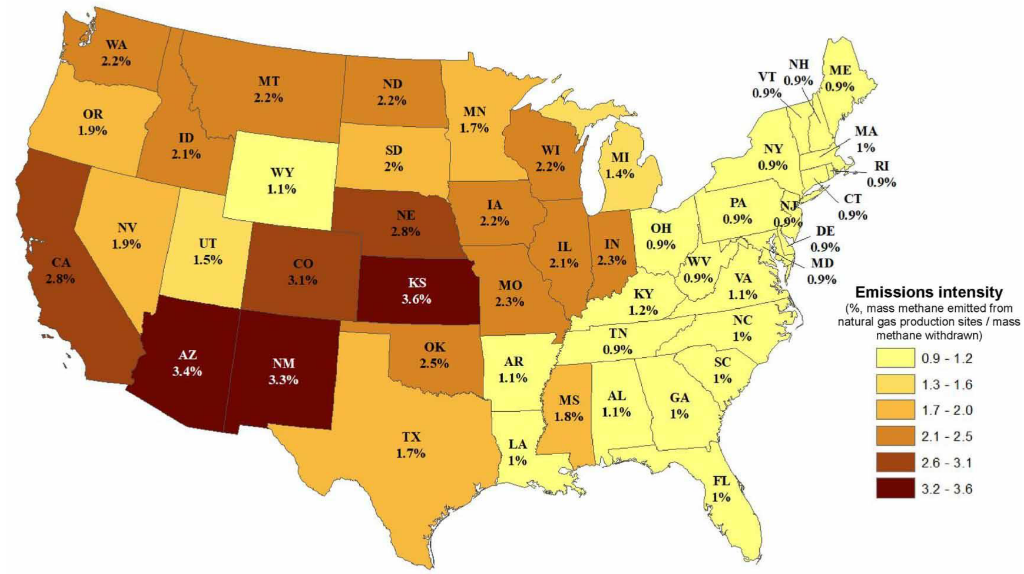

Figure 3. Estimated consumption-normalized production-stage methane emissions for natural gas consumed in each state. *Source*: Burns and Grubert (2021).

Table 3. Estimates of non-production-stage methane emissions across oil and natural gas industry segments and converted leakage rates used to assess fugitive emissions in Scout.

Industry segment	Alvarez et al. estimate of 2015 CH_4 (Tg/yr)	Converted methane leakage rate[1]
Gathering	2.6	0.46%
Processing	0.72	0.13%
Transmission & Storage	1.8	0.32%
Local Distribution	0.44	0.08%
Oil Refining and Transportation	0.034	0.01%

[1]Based on estimated total natural gas production in 2015 of 565 Tg (Alvarez et al. 2018).

We add state-level production-stage leakage rates to US national averages for the remaining oil and natural gas industry segments, which we assume decrease proportionally with production-stage decreases, to calculate total methane leakage factors by state. After determining state-level leakage rates based on this approach, we apply these to reference case and alternate scenario estimates of energy consumption where the fuel type is natural gas. Given that the leakage rates apply to the volume of methane leaked from natural gas production, we convert natural gas consumption in MMBtu to volume using a conversion factor of 1.037 MMBtu = 1,000 ft^3 (EIA 2021). We then apply the state-level leakage rates to calculate volume of methane leaked.[6]

[6] We convert to mass using the specific volume of methane at 70 degrees Fahrenheit, 1 atmosphere of

Fugitive emissions sensitivity parameters. Our analysis explores sensitivities in fugitive emissions estimates by varying settings for key parameters in both the fugitive refrigerant and methane calculations.

To examine sensitivities in our projections of refrigerant emissions, we compare cases of differing regulatory assumptions relevant to the availability and use of high-GWP refrigerants and specific low-GWP alternatives. We consider a less stringent case, which models the continued use of typical, higher-GWP equipment refrigerants as of 2020 without a defined phase-out plan, as well as a more stringent case that represents an immediate transition to low-GWP refrigerants beginning in 2024. Table 2 summarizes the typical and low-GWP alternative refrigerants for key technologies in our analysis. Again, the low-GWP assumptions are based on refrigerant regulations that pre-date passage of the AIM Act.

To assess a range of methane leakage assumptions, we integrate lower- and upper-bound state-level, production-stage methane leakage rates from Burns and Grubert (2021). These assumptions are based on methane emissions from major O&NG basins in Omara et al. (2018), as well as lower- and upper-bound assumptions on leakage rates for methane imported from Canada (1–3%).

Results

Baseline projections of fugitive refrigerant and methane emissions

Figure 4 (see also Table A1) shows that the fugitive refrigerant and methane emissions from residential building end uses are substantial but considerably smaller in magnitude than the operational emissions from onsite fossil fuel combustion and electricity generation for residential building end uses. Worst-case assumptions include weak GWP policy and high methane leakage rates, with reference case power grid development. Under these worst-case assumptions, fugitive emissions are one third the size of operational emissions in 2050 and comprise about one quarter of total 2050 residential CO_2e emissions across all sources included (left side of Figure 4).[7] Best-case assumptions include strong GWP policy and low methane leakage with a reference case grid. Under these best-case assumptions, fugitive sources are 19% as large as operational emissions in 2050 and comprise 16% of total 2050 residential emissions across all sources (right side of Figure 4).

Operational emissions in Figure 4 reflect an electricity emissions scenario that assumes current policy support without future extension, resulting in near-term reductions in electricity emissions that begin to plateau around 2040. More aggressive assumptions about electricity decarbonization would increase the relative influence of the residential fugitive emissions components. Under the most extreme case, where the U.S. power sector meets the Biden Administration target of a 100% clean electricity supply by 2035, residential fugitive emissions would be up to 53% of operational emissions in 2050[8] and fugitive emissions would comprise

pressure (20.2 g/ft^3). Finally, we use the GWP-100 value of methane (28) to convert to CO_2e emissions.

[7] Embodied emissions from residential construction and materials are out of the scope of this study.
[8] Under this grid scenario, residential operational emissions would come entirely from onsite fossil fuel combustion.

Figure 4. Worst-case (left panel) and best-case (right panel) estimates of total fugitive methane and refrigerant leakage emissions from U.S. residential building energy consumption from 2024-2050, compared to total operational emissions from direct on-site combustion of fossil fuels and indirect generation of electricity for residential building end uses, under a reference case.

35% of all residential emissions sources. This assumes worst-case methane leakage rates and refrigerant GWP values.

Across cases, methane leakage is the larger of the two fugitive components, at 55% and 67% of total baseline fugitive emissions under best- and worst-case assumptions, respectively. Uncertainty about refrigerant GWP values has a larger effect on results than uncertainty about methane leakage rates. Total baseline refrigerant emissions in 2050 decrease by 57% from the worst to the best case (an absolute range of ~40 Mt CO_2e), versus a 32% decrease in the same fugitive methane emissions estimate between these cases (an absolute range of ~28 Mt CO_2e).

The 57% decrease in refrigerant emissions from the use of lower GWP refrigerants falls short of the 85% HFC consumption reduction target in the AIM Act, even before considering added refrigerant emissions from electrification beyond the reference case (see below).[9] This suggests that refrigerant GWPs will need to decrease beyond the recent market trends and pre-AIM Act regulations we represent in our analysis to be compatible with an AIM Act future.

Fugitive refrigerant emissions under high electrification

Figure 5 (see also Table A2) shows that high residential building electrification will increase fugitive refrigerant emissions through 2050. However, these increases are outweighed by concurrent reductions in operational emissions and, to a lesser degree, by reductions in fugitive emissions from methane leakage.

The least favorable refrigerants case assumes high equipment electrification with higher-GWP refrigerants, low offset from avoided methane leakage, and higher-emissions electricity

[9] An 85% reduction in HFC production and consumption in 2036 will reduce the GWP of equipment on the market in that year, rather than the installed base of existing equipment to be replaced. Achieving an 85% reduction by 2050 would require full turnover of the existing equipment stock in the span of 14 years, but some equipment lifetimes may be 20 years or more (e.g., furnaces and other heating equipment).

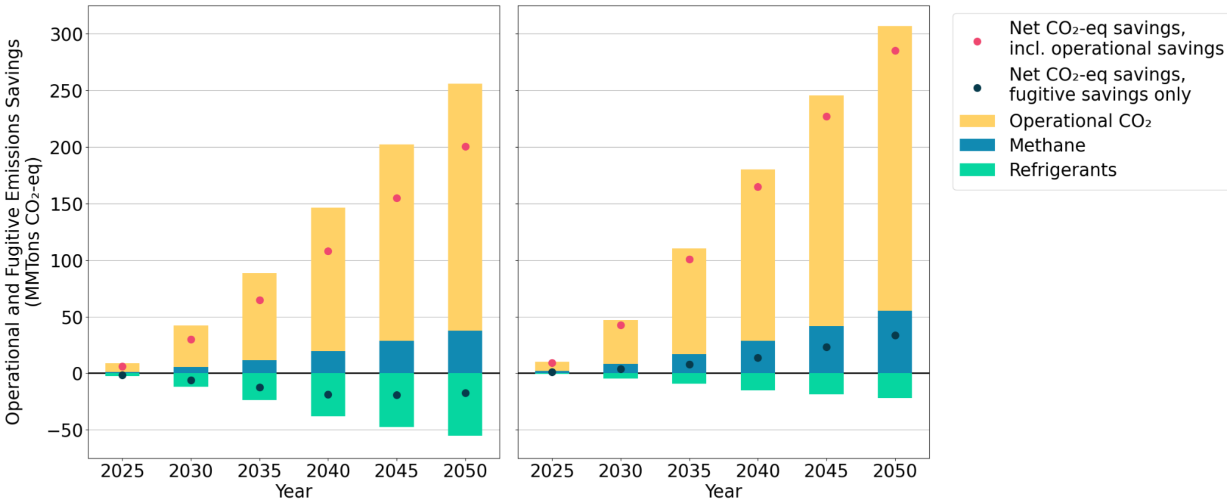

Figure 5. U.S. residential building operational and fugitive methane emissions savings from high residential electrification vs. concurrent increases (e.g., negative savings) in fugitive refrigerant leakage emissions, from 2024-2050, under least favorable (left panel) and most favorable (right panel) assumptions from a refrigerant emissions perspective.

supply (left side of Figure 5). This least favorable refrigerants case still results in net emissions savings of 200 Mt CO_2e by 2050. Moreover, emissions savings are only slightly negative when considering the net of fugitive components alone (–18 Mt CO_2e). Even under these conservative assumptions, operational emissions savings from high residential electrification in 2050 are about four times greater than added refrigerant leakage emissions.

The most favorable refrigerants case assumes high equipment electrification and lower-GWP refrigerant alternatives, with high offsets from avoided methane leakage and an electricity supply that is 100% clean by 2035 (right side of Figure 5). This most favorable refrigerants case results in net emissions savings of 285 Mt CO_2e. Net savings for the fugitive components alone are also positive at 34 Mt CO_2e. Given these optimistic assumptions, operational savings from high residential electrification in 2050 are eleven times greater than added refrigerant leakage emissions.

Added refrigerant emissions from high residential electrification are clearly outweighed by concurrent emissions savings benefits (from operational and fugitive methane sources). However, these added emissions exacerbate the potential gap noted above between residential refrigerant emissions levels in 2050 and AIM Act HFC reduction targets. Meeting the AIM Act targets will require shifting refrigerants towards non-HFC alternatives that have ultra-low-GWP characteristics (GWP<10). If achieved, such a shift would effectively nullify the refrigerant emissions impact of most added units of electric equipment and draw total residential refrigerant emissions closer to zero, with the timing of the decline determined by the speed with which ultra-low-GWP refrigerants become typical on the market and the rate at which existing equipment is replaced.

Conclusions

Our results demonstrate that fugitive GHG emissions from leakage in residential building equipment refrigerants and the residential gas supply are significant and will grow in importance as operational building emissions decrease over time.[10] We find that fugitive emissions sources constitute up to about one quarter of all residential building emissions[11] given weak policy intervention on refrigerant GWPs, high rates of methane leakage, and a reference case power grid. In this case, the fugitive refrigerant and methane components are similar in magnitude.

There is substantial uncertainty in the projections of fugitive emissions, however. The fugitive sources could comprise less than 20% of residential emissions, given less aggressive grid decarbonization, low rates of methane leakage, and stronger policy support for reducing refrigerant emissions. On the other hand, the fugitive share of the total could also be greater than 30% of residential emissions if the power grid is fully decarbonized alongside worst-case developments for the fugitive emissions sources.

Our findings underscore that fugitive sources of residential building emissions will be important to account for in future modeling of energy system decarbonization. Estimating refrigerant emissions is critical in decarbonization scenarios with high building electrification, which will increase total residential refrigerant emissions. However, the degree of the increase depends strongly on assumed refrigerant characteristics. Lower-GWP refrigerant use avoids more than 50% of worst-case increases in refrigerant emissions. Moreover, we show that across all projection years and sensitivity cases, the additional refrigerant emissions from high electrification are far lower than the operational emissions savings from switching fossil-based equipment to clean electricity and the fugitive methane emissions avoided by reducing natural gas consumption (~7–21% as large). The avoided methane benefit can be excluded, given uncertainties about the relationship between consumption and methane leakage (e.g., in Sargent et al. (2021)). Even excluding this benefit, however, the scale of operational emissions benefits from electrification is four to eleven times larger than potential refrigerant emissions increases.

Policy makers can use our findings to emphasize residential electrification as a no-regrets emissions reduction strategy and to counter concerns about refrigerants that may hinder support for high-electrification futures. At the same time, our results demonstrate the need for concerted efforts to further limit refrigerant leakage emissions. Specifically, our most optimistic trajectory for residential refrigerant emissions may be less aggressive than one suggested by HFC reduction targets in the AIM Act – even assuming the use of low-GWP refrigerants and before considering refrigerant increases from electrification. Measures that bring typical refrigerant GWPs below the low-GWP levels assumed in our study will be essential for meeting the latest legislated refrigerant emissions targets in a highly electrified future. Such measures include including ultra-low-GWP refrigerant alternatives; reducing refrigerant leakage rates through improved leakage detection, repair and prevention; and increasing refrigerant recovery and reuse..

Our analysis did not consider the full range of uncertainties associated with fugitive emissions accounting, including uncertainties about refrigerant leakage rates, which will vary by equipment type, or further uncertainties about methane leakage rates, which may be larger than previously estimated (Sargent et al. 2021). It is also inherently difficult to predict which specific

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[10] Operational emissions are expected to decline through reductions in electricity emissions intensity, increased building efficiency, and the conversion of fossil-fired building equipment to run on clean electricity.

[11] Again, excluding embodied life cycle emissions sources.

low-GWP alternatives might replace typical refrigerants in future years for different equipment types. Given these considerations, our estimates are intended to convey rough scales of relative magnitude and sensitivity rather than to serve as predictions of the future. Follow-on work will continue evaluate sensitivities and comparisons across the buildings sector and will examine regional variability. We also intend to further develop model inputs and emissions estimates to represent the AIM Act and its potential to mitigate building refrigerant emissions impacts in a high electrification future.

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Appendix

Table A1. Data values for Figure 4.

	Worst case for fugitive refrigerants/methane				Best case for fugitive refrigerants/methane			
Year	Fossil	Electricity	Refrigerants	Methane	Fossil	Electricity	Refrigerants	Methane
2025	314.08	407.54	48.30	88.74	314.08	407.54	45.93	60.82
2030	313.61	216.47	53.12	89.69	313.61	216.47	40.16	61.48
2035	308.23	172.01	57.70	88.67	308.23	172.01	36.07	60.78
2040	304.70	138.16	62.16	88.20	304.70	138.16	33.31	60.45
2045	302.94	125.34	66.52	88.21	302.94	125.34	31.46	60.43
2050	301.15	165.75	70.77	88.02	301.15	165.75	30.37	60.26

Table A2. Data values for Figure 5.

	Least favorable for refrigerant emissions					Most favorable for refrigerant emissions				
Year	Refrigerants	Methane	Operational	Net (fugitive only)	Net (all sources)	Refrigerants	Methane	Operational	Net, (fugitive only)	Net (all sources)
2025	-2.66	1.22	7.58	-1.43	6.15	-0.69	1.81	8.28	1.13	9.40
2030	-11.90	5.67	36.35	-6.23	30.12	-4.69	8.39	38.85	3.70	42.55
2035	-23.76	11.53	76.94	-12.23	64.71	-9.34	16.99	93.21	7.66	100.87
2040	-38.35	19.61	126.63	-18.74	107.89	-15.01	28.82	151.17	13.81	164.97
2045	-47.68	28.59	173.88	-19.10	154.78	-18.77	41.93	203.79	23.15	226.94
2050	-55.34	37.84	218.05	-17.50	200.55	-21.71	55.46	251.59	33.75	285.35