Comparison of Operational Costs and Carbon Emissions for Gas and Electric Heat Pumps at Commercial Buildings

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Table of Contents

ICF

Executive Summary

Heat pump technologies at commercial buildings can significantly reduce carbon emissions and save on energy costs compared to incumbent heating and cooling systems. Commercial buildings typically use standard rooftop units, with configurations that can vary depending on climate. For this analysis, small-to-medium commercial buildings were modeled with incumbent rooftop units (RTUs) consisting of gas furnaces for heating and electric chillers for cooling and compared to three different heat pump options.

Both electric heat pumps (EHPs) and gas heat pumps (GHPs) can be used year-round for both heating and cooling, at higher efficiencies than typical incumbent systems. In this study, ICF evaluated the performance of four equipment options for stand-alone retail stores and medium-sized office buildings.

- Incumbent RTU heating and cooling systems (gas-fueled furnace and Trane electric chiller)
- Absorption gas heat pump: Robur RTAR360-720
- Engine-driven gas heat pump: Aisin E Model
- Electric heat pump: Trane TWA180B

The performance of heat pumps depends on ambient outdoor temperature. EHPs have higher cooling efficiencies in hot weather while GHPs perform more efficiently in cold weather conditions. EHPs have significantly higher coefficients of performance than GHPs. However, the primary fuel source for EHPs is typically fossil fuels consumed at utility power plants with conversion efficiencies under 40 percent. When combined with grid transmission and distribution losses, the effective efficiencies of EHPs are often comparable to GHPs. Under many conditions, gas heat pumps can use less fuel and produce fewer greenhouse gas emissions than electric heat pumps.

In this study, the effects of ambient temperatures in different climate zones – along with regional marginal electric grid emissions and local energy prices – were measured in terms of expected carbon emissions and operational costs over a 20-year life cycle in the following U.S. locations:

- Baltimore (Mixed-Humid)
- Houston (Hot-Humid)
- Minneapolis (Cold)
- Las Vegas (Hot-Dry)

ICF used U.S. Energy Information Administration (EIA) average commercial prices for electricity and natural gas along with grid emissions estimates from 2021-2040 by eGRID region[1] to measure the relative differences in operational costs and emissions impacts over the 20-year period as regional grids incorporate more renewable resources. ICF also applied assumptions related to renewable natural gas (RNG) percentage of U.S. natural gas supply.[2]

The results showed that gas heat pumps offered the lowest-cost option producing the lowest total emissions over the 20-year period in each of the evaluated locations. Absorption GHPs offered the lowest costs and emissions associated with heating, while engine-fired GHPs offered the lowest costs and emissions associated with cooling as well as the lowest overall costs and emissions. The modeled

[1] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[2] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

EHPs performed favorably for cooling compared to incumbent systems, but higher electricity costs and relatively high marginal grid emissions prevented EHPs from achieving the lowest costs or emissions over the analysis period. Figure ES-1 shows the average operating cost reduction for absorption GHPs, engine-driven GHPs, and EHPs compared to the incumbent RTU system.

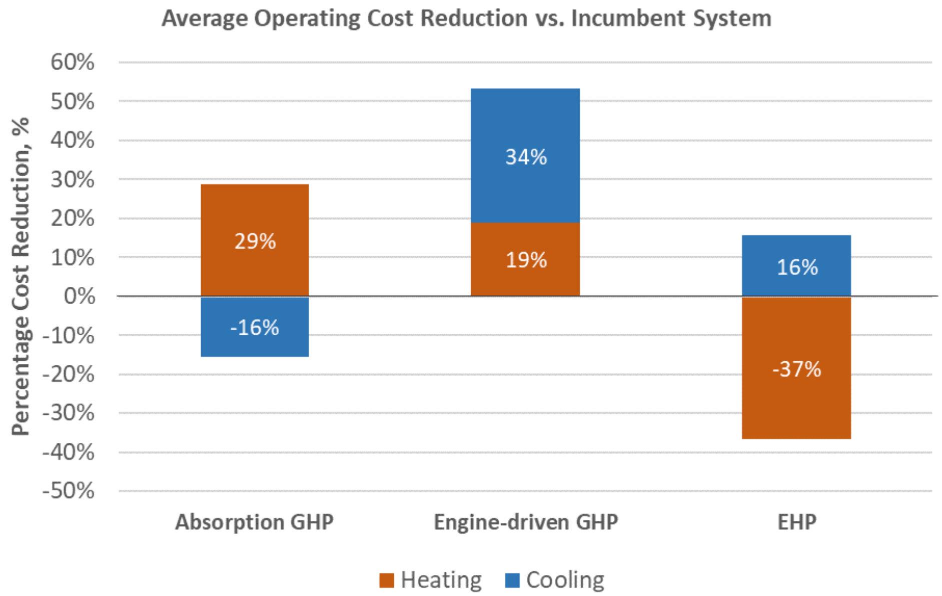


Figure ES-1. Average 20-Year Operating Cost Reduction for Heat Pumps compared to Incumbent Systems

In Figure ES-2, the average carbon emissions reductions for each heat pump option are compared to carbon emissions from the incumbent RTU heating and cooling system over the 20-year period.

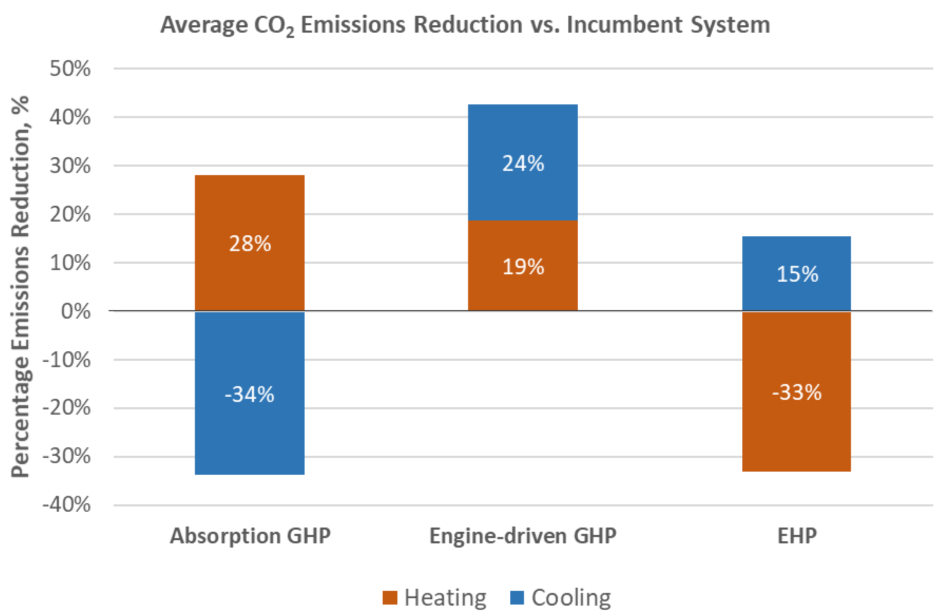


Figure ES-2. Average 20-Year Carbon Emissions Reduction for Heat Pumps compared to Incumbent Systems

The results of this study showed that engine-driven GHPs can operate with lower operating costs and produce fewer carbon emissions the incumbent system and EHPs in commercial applications. Absorption GHPs can offer lower costs and emissions on the heating side, and EHPs perform more favorably than both GHP options for cooling. However, most buildings have significant demands for both heating and cooling, and engine-driven GHPs were found to be the most well-rounded option, offering the lowest total costs and carbon emissions.

While EHPs have been a large focus of recent decarbonization policies and programs, GHPs may be better suited for many buildings and climates, with equivalent or reduced carbon emissions when considering the marginal grid resources used to power EHPs. As the electric grid gets greener, the associated emissions for EHPs will be reduced, but at the same time renewable natural gas (RNG) and potentially zero-carbon hydrogen will be incorporated into the natural gas supply in increasing percentages, reducing the carbon impact of GHPs. The effects of increased decarbonization of both the grid and the natural gas supply were taken into account for this study, with an average 19% reduction in grid carbon emissions and 13% increase in RNG supply by 2040.

There are pathways for both EHPs and GHPs to decarbonize the commercial sector. Policymakers should consider the current benefits of GHPs, specifically the ability to reduce carbon emissions now, with a low operational cost. GHPs can be especially effective in areas with cold climates and existing gas infrastructure. The carbon benefits of GHPs – compared to options using grid electricity – are expected to extend into the future while natural gas or other fossil fuels are used as marginal grid resources. All of these considerations are especially important when designing regional, state, and local decarbonization policies and programs.

I. Introduction

ICF performed an analysis to determine the differences in operational costs and carbon emissions for four different heating and cooling equipment options. Options were evaluated for small-to-medium-sized commercial buildings in different locations with varying energy costs and grid emissions attributes. Equipment options included typical incumbent systems and three types of heat pumps.

- Typical incumbent heating and cooling systems (gas heating and electric cooling)
- Absorption gas heat pump
- Engine-driven gas heat pump
- Electric heat pump

ICF modeled the performance of these equipment options to serve a stand-alone retail establishment, and a medium-sized office building in four different locations. The resulting operational costs and carbon emissions were calculated over a 20-year period to represent typical equipment life. Results were then compared to determine the options with the lowest operational cost and lowest carbon emissions impact.

For this high-level analysis of expected costs and emissions, four locations in distinct climate zones and energy markets were chosen, and several assumptions were applied. This document lays out the methodology and assumptions used in the analysis, presents the results for each heat pump application, and provides key takeaways from the findings.

II. General Methodology and Assumptions

This section summarizes the analysis carried out by ICF to characterize the economic and environmental characteristics of gas heat pumps (GHPs), electric heat pumps (EHPs) and incumbent heating and cooling technologies over a twenty-year period. The analysis was carried out for stand-alone retail stores and medium-sized office buildings from 2021 to 2040 in the following four locations:[3]

- Baltimore (Mixed-Humid)
- Houston (Hot-Humid)
- Minneapolis (Cold)
- Las Vegas (Hot-Dry)

ICF selected the above locations to simulate the technical performance of gas and electric heat pumps in a variety of climatic conditions. The selected locations also have differences in electricity and gas prices, and in electric grid emission rates, which would impact the overall economics and emissions of heat pumps over the analysis timeframe. ICF used DOE Commercial Reference Building models to develop hourly energy profiles and temperatures for the four chosen locations.[4] Equipment specifications for the following equipment options, representing typical choices for small commercial applications, were applied to the heating and cooling loads to determine the amount of gas and/or electricity required during each hour. Appendix A includes detailed equipment specifications applied to the analysis.

[3] Throughout this report, ICF uses the terminology 'analysis case' to refer to individual combinations of analysis locations and building applications. For instance, medium office in Baltimore is one of the eight 'analysis cases' included in this study.
[4] Commercial Reference Buildings: Office of Energy Efficiency and Renewable Energy, Department of Energy. Available at: https://www.energy.gov/eere/buildings/commercial-reference-buildings

- Standard gas-fueled furnace and Trane electric chiller
- Robur RTAR360-720 absorption gas heat pump
- Aisin E Model gas heat pump
- Trane TWA180B electric heat pump

Electricity and fuel consumption values were combined with average electricity and gas prices from EIA to determine energy costs for each equipment option. ICF applied EIA escalation rates to the 2019 or 2020 average prices to determine 2021 pricing. Future-looking forecasts from the EIA Annual Energy Outlook have electricity and gas prices remaining relatively flat over the next twenty years, generally increasing along with inflation. ICF internal forecasts are generally in agreement, and due to the uncertainty in future price impacts of renewable energy mandates, prices are assumed to remain flat relative to inflation for the analysis period.

Emissions associated with each equipment option were calculated by applying the following factors:

- 116.9 lbs of CO_2/MMBtu for carbon emissions from natural gas consumption
- eGRID non-baseload 2018 emission factors, incrementally reduced according to assumptions applied in 2020 CHP Emissions report prepared by ICF.[5]
    - Estimated emission factors through 2050 by eGRID subregion (more accurate than state-level estimates by capturing interstate transactions in regional grid networks)
    - Applied energy policies, economic modeling, and legislated 100% zero-carbon mandates

As marginal resources on the electric grid become cleaner, the supply of natural gas is also expected to become cleaner through increased production of Renewable Natural Gas (RNG) . To characterize the increasing supply of zero-carbon RNG in this analysis, ICF utilized the findings of a study prepared for the American Gas Foundation (AGF) that provides estimates for economy-wide RNG production up to 2040.[6] RNG production estimates consistent with the 'high production scenario' outlined in the AGF study are used in this analysis. ICF estimates that in the high RNG production scenario, RNG will make up approximately 13 percent of economy-wide natural gas consumption in 2040. The proportion of gas consumption equivalent to RNG production in each year is assumed to carry zero emissions.

Zero-carbon hydrogen resources are also expected to be developed and incorporated into the natural gas supply in the future, although the quantity and timing on the availability of these resources is not available at this time ICF did not make any assumptions related to zero-carbon hydrogen in the natural gas supply over the study period.

While the coefficient of performance of electric heat pumps tends to exceed that of gas heat pumps by a large margin – particularly in cooling mode – this does not consider the losses associated with producing and delivering the electricity. When these are considered, the total emissions associated with GHPs are often lower than EHPs.

The grid emissions assumptions applied for each location are shown in Table 1. A grid loss factor of 5.1% was also added.

[5] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[6] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

Table 1: Electricity Grid Emission Factors Applied in the Analysis

Modeled Building Location	eGRID Region Applied	2021 Emission Factor (lb/MWh)	2040 Emission Factor (lb/MWh)	Marginal Grid Emissions Carbon Reduction
Baltimore, MD	RFCE	1,234	1,180	4.4%
Houston, TX	ERCT	1,222	1,004	17.8%
Las Vegas, NV	NWPP	1,487	977	34.3%
Minneapolis, MN	MROW	1,700	1,343	21.0%

The estimated operational costs and emissions for each equipment option are then compared over the 20-year period. More details on the analysis methodology and assumptions are provided in Appendix A.

III. Results and Discussion

In this section, ICF presents an initial summary of findings of the analysis followed by detailed economic and environmental results for retail stores and medium-sized offices in each of the four analysis locations.

Summary of Findings

ICF carried out an operational cost and emissions analysis for a 20-year period from 2021-2040 to compare the performance of engine-drive and absorption GHPs with the incumbent HVAC (heating/ventilating/air conditioning) options in medium-sized offices and retail stores in Baltimore, Houston, Las Vegas, and Minneapolis. ICF analyzed the comparative economic and environmental performance of the heat pump options altogether and in heating and cooling modes individually. ICF also modeled the operating economics and emissions of EHPs in this study to provide an additional benchmark for comparison. The summary findings of this analysis are detailed below.

20-year Operating Expenses

ICF analyzed the 20-year cost of operation (in 2021$) of each heat pump option and the incumbent HVAC system in medium-sized offices and retail stores in each analysis location. ICF's analysis showed that absorption GHPs offer the lowest heating costs, while engine-driven GHPs offer the lowest cooling and overall costs of operation in medium-sized offices and retail stores in each analysis location. It is noted that in all the analysis cases, GHPs offer better overall operating economics compared to EHPs. In ICF's assessment, this can be attributed to the lower efficiency of EHPs in heating mode particularly in low ambient temperature conditions, and the relatively low cost of natural gas compared to electricity.

While this study applied average electricity rates, many electric utilities have high electricity rates or demand charges during the summer cooling season that serve to increase electricity costs. Conversely, gas utilities may offer lower rates for cooling applications in summer months, as this is traditionally when gas demand is at its lowest. These factors could lead to more economic advantages for GHPs compared to EHPs.

Figure 1, Figure 2,

Figure 3 andFigure 4 below show the total 20-year cost of operation (in 2021$) of the incumbent HVAC system, absorption GHP, engine-driven GHP and the EHP in retail stores in each of the four analysis locations. The total operating costs are broken down into heating and cooling costs. As noted above, the charts below show that engine-driven GHPs have the lowest total cost of operation over 20-years in retail stores in all four analysis locations.

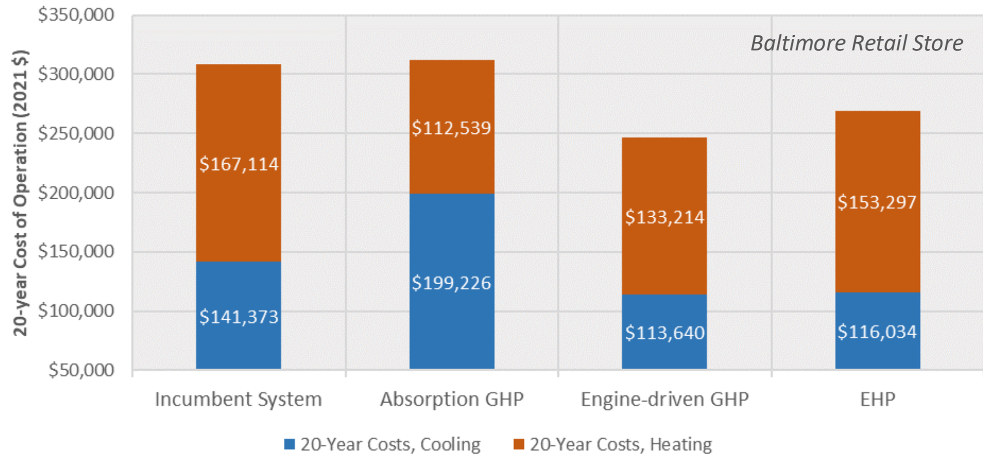


Figure 1: 20-Year Operating Cost Estimates for the Heat Pump and Incumbent Options in Retail Stores - Baltimore

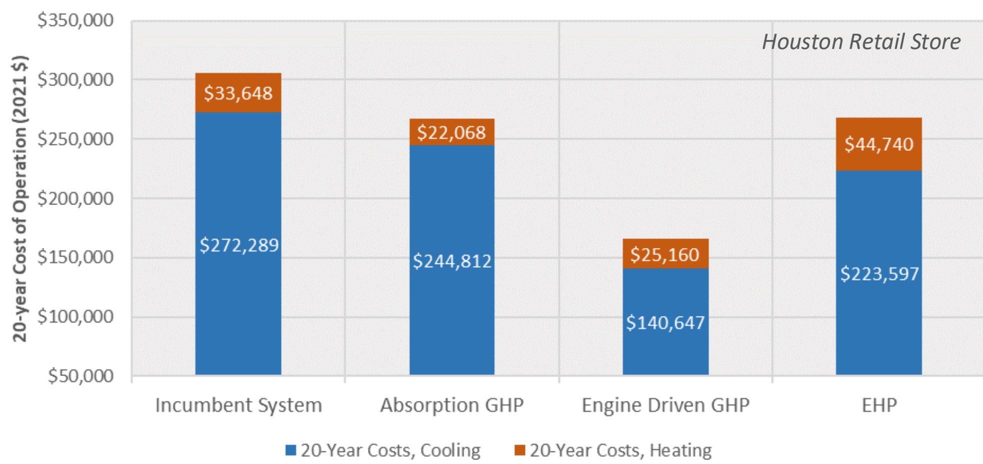


Figure 2: 20-Year Operating Cost Estimates for the Heat Pump and Incumbent Options in Retail Stores – Houston

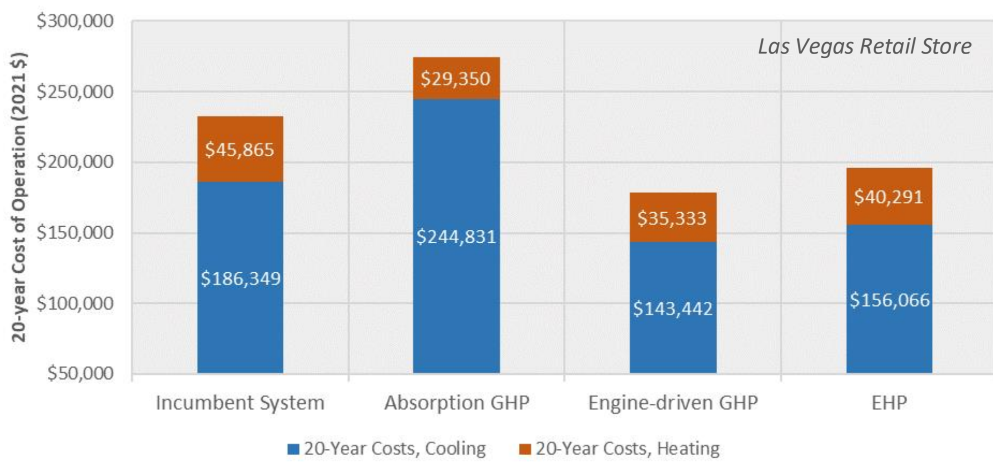


Figure 3: 20-Year Operating Cost Estimates for the Heat Pump and Incumbent Options in Retail Stores – Las Vegas

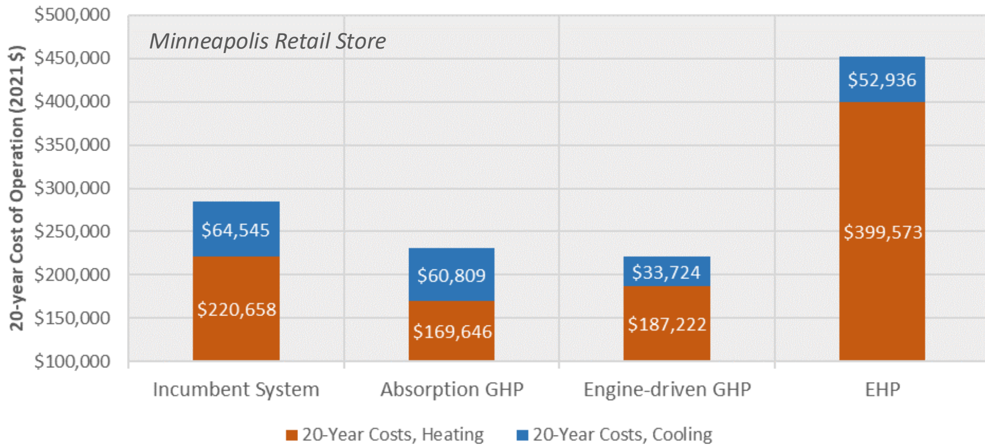


Figure 4: 20-Year Operating Cost Estimates for the Heat Pump and Incumbent Options in Retail Stores - Minneapolis

ICF observed similar results for medium-sized office buildings with the absorption GHP offering the lowest cost heating, and the engine-driven GHP offering the lowest cooling and overall costs. Table 2 and Table 3 below show the 20-year operating costs of each technology option for retail stores and medium-sized offices, respectively with heating and cooling cost breakdowns. The numbers in bold represent the lowest cost technology for heating, cooling, or total costs for each location.

Table 2: 20-year Cost of Operation of Heat Pump and Incumbent Systems in Retail Stores (2021 dollars)

		Incumbent System	Absorption GHP	Engine-Driven GHP	EHP
Baltimore	Heating Costs	$167,114	**$112,539**	$133,214	$153,297
	Cooling Costs	$141,373	$199,226	**$113,640**	$116,034
	Total	$308,487	$311,765	**$246,854**	$269,331
Houston	Heating Costs	$33,648	**$22,068**	$25,160	$44,740
	Cooling Costs	$272,289	$244,812	**$140,647**	$223,597
	Total	$305,937	$266,880	**$165,807**	$268,336
Las Vegas	Heating Costs	$45,865	**$29,350**	$35,333	$40,291
	Cooling Costs	$186,349	$244,831	**$143,442**	$156,066
	Total	$232,214	$274,182	**$178,775**	$196,357
Minneapolis	Heating Costs	$220,658	**$169,646**	$187,222	$399,573
	Cooling Costs	$64,545	$60,809	**$33,724**	$52,936
	Total	$285,202	$230,456	**$220,946**	$452,509

Table 3: 20-year Cost of Operation of Heat Pump and Incumbent Systems in Medium-sized Offices (2021 Dollars)

		Incumbent System	Absorption GHP	Engine-Driven GHP	EHP
Baltimore	Heating Costs	$117,224	**$78,723**	$92,542	$106,939
	Cooling Costs	$315,459	$453,574	**$252,185**	$268,065
	Total	$432,683	$532,297	**$344,727**	$375,004
Houston	Heating Costs	$41,271	**$26,609**	$29,623	$51,771
	Cooling Costs	$470,586	$433,406	**$244,032**	$400,079
	Total	$511,857	$460,015	**$273,655**	$451,850
Las Vegas	Heating Costs	$48,278	**$30,648**	$36,517	$41,459
	Cooling Costs	$393,367	$524,799	**$304,266**	$339,682
	Total	$441,645	$555,447	**$340,783**	$381,141
Minneapolis	Heating Costs	$185,354	**$142,879**	$157,119	$337,009
	Cooling Costs	$153,436	$148,127	**$80,365**	$130,318
	Total	$338,789	$291,006	**$237,484**	$467,327

Figure 5 shows a summary of the average cost reduction of absorption GHPs, engine-driven GHPs and EHPs compared to the incumbent RTU system across all four analysis locations. On average, absorption GHPs offer the highest heating cost reductions compared to the incumbent system, while engine-driven GHPs offer the highest overall cost reductions including heating and cooling.

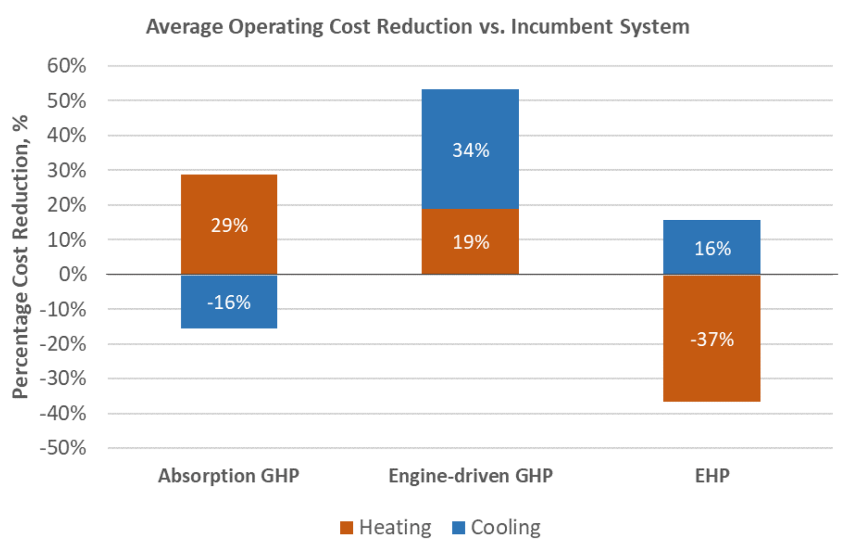


Figure 5: Operating Cost Percentage Reduction by Technology Compared to Incumbent RTU System

Note that this analysis only considered average electricity and gas costs. Often, electric rates have demand and/or time-of-use components that can increase the impact of electricity used for cooling in summer months. ICF assessed the impact of GHPs and EHPs on summer peak demand. On average, GHPs reduced the summer peak by about 50 percent while EHPs – with improved efficiencies compared to incumbent systems – reduced the summer peak by approximately 10 percent. Depending on electric utility rate structures, this could lead to greater cost savings for GHPs compared to EHPs.

20-year Cumulative Emissions

ICF analyzed the 20-year cumulative CO_2 emissions of each heat pump option and the incumbent HVAC system in medium-sized officed buildings and retail stores by taking into account the changes in electric and gas emission rates over the 20-year analysis period in each location. ICF's analysis showed that in both medium-sized office buildings and retail stores, absorption GHPs offer the lowest emissions in the heating-only mode, while engine-driven GHPs offer the lowest cooling and overall emissions in all four analysis locations. EHPs are seen to have higher overall emissions than the engine-driven GHP in all locations and lower emissions than the incumbent HVAC system in Baltimore, Houston and Las Vegas. In Minneapolis, where coal power generation forms a large fraction of grid electricity supply, EHPs have higher overall emissions compared to the incumbent HVAC system.

Figure 6, Figure 7, Figure 8 and Figure 9 below show the 20-year cumulative CO_2 emissions of GHPs compared to the incumbent HVAC system and EHPs in retail stores. The 20-year total emissions are broken down into heating and cooling emissions. As noted above, the charts below show that engine-driven GHPs have the lowest cumulative operational emissions in retail stores in all four locations over the analysis period.

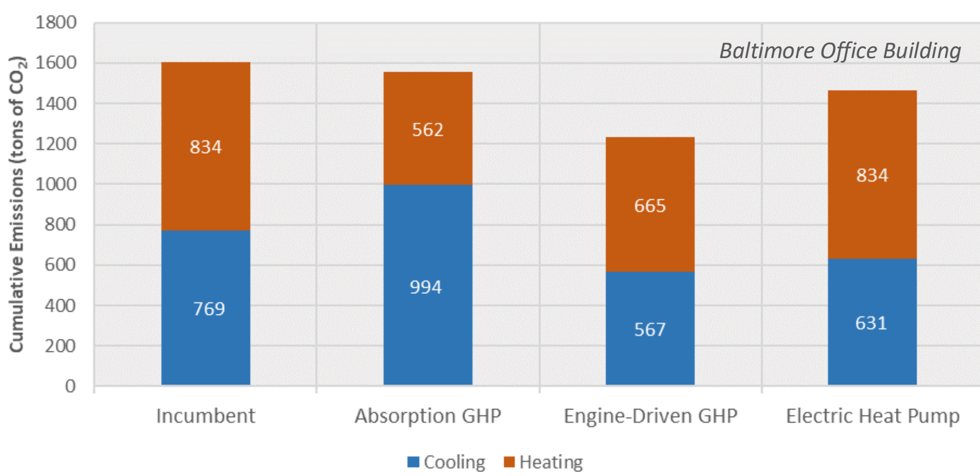


Figure 6: 20-Year Operating Cost Estimates for the Heat Pump and Incumbent Options in Retail Stores - Baltimore

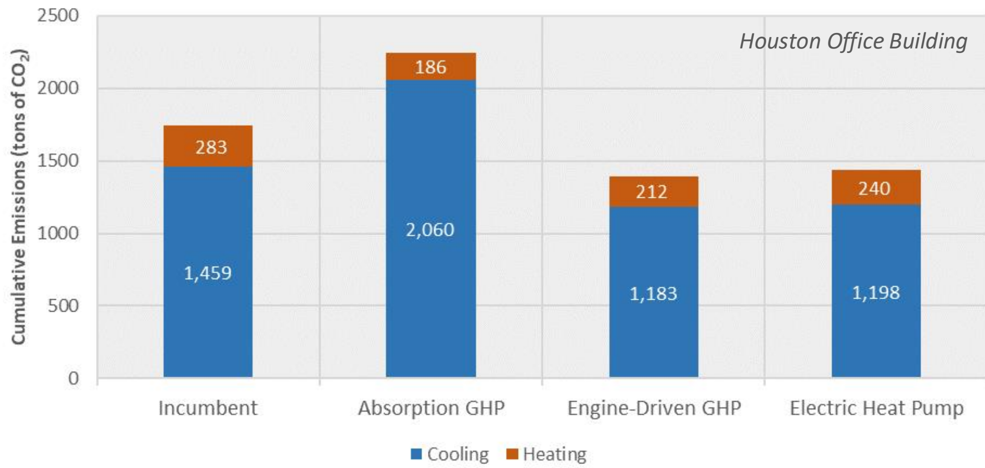


Figure 7: 20-Year Operating Cost Estimates for the Heat Pump and Incumbent Options in Retail Stores - Houston

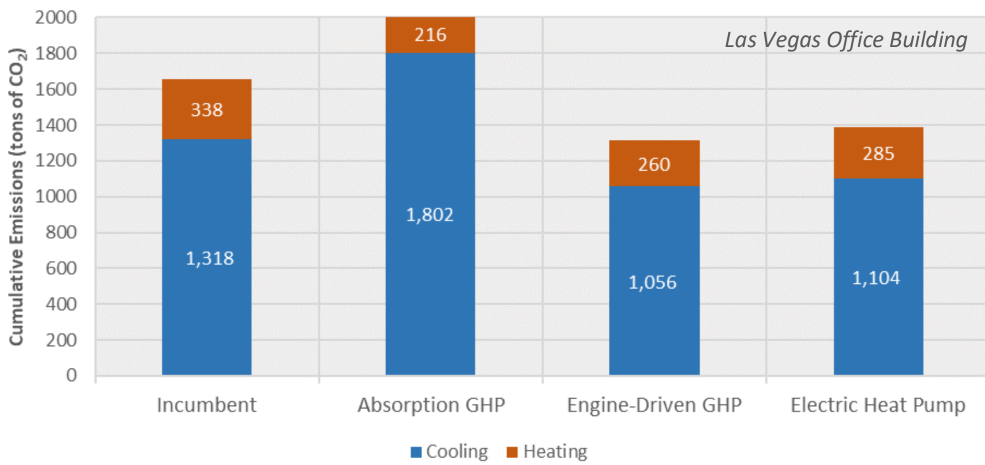


Figure 8: 20-Year Operating Cost Estimates for the Heat Pump and Incumbent Options in Retail Stores - Las Vegas

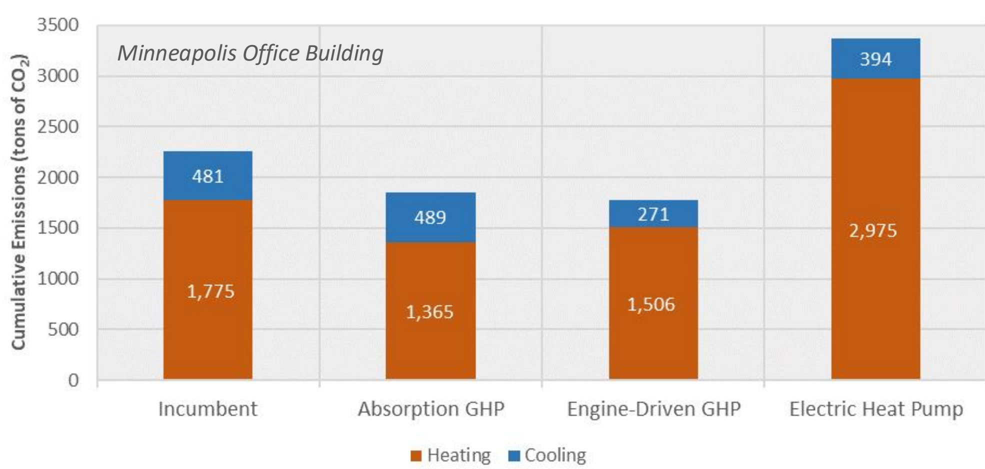


Figure 9: 20-Year Operating Cost Estimates for the Heat Pump and Incumbent Options in Retail Stores - Minneapolis

ICF observed similar results for medium-sized office buildings with the absorption GHP producing the lowest heating emissions, and the engine-driven GHP producing the lowest cooling and overall CO_2

emissions. Table 4 and Table 5 below show the 20-year operating emissions of each technology option for retail stores and medium-sized offices, respectively with heating and cooling emission breakdowns. Values in bold represent the technology with the lowest carbon emissions for each location.

Table 4: 20-year Cumulative Emissions of Heat Pump and Incumbent Systems in Retail Stores (tons of CO_2)

		Incumbent System	Absorption GHP	Engine-Driven GHP	EHP
Baltimore	Heating Emissions	834	**562**	665	834
	Cooling Emissions	769	994	**567**	631
	Total Emissions	1,603	1,556	**1,232**	1,465
Houston	Heating Emissions	283	**186**	212	240
	Cooling Emissions	1,459	2,060	**1,183**	1,198
	Total Emissions	1,742	2,245	**1,395**	1,438
Las Vegas	Heating Emissions	338	**216**	260	285
	Cooling Emissions	1,318	1,802	**1,056**	1,104
	Total Emissions	1,655	2,018	**1,316**	1,389
Minneapolis	Heating Emissions	1,775	**1,365**	1,506	2,975
	Cooling Emissions	481	489	**271**	394
	Total Emissions	2,255	1,854	**1,777**	3,369

Table 5: 20-year Cumulative Emissions of Heat Pump and Incumbent Systems in Medium-sized Offices

		Incumbent System	Absorption GHP	Engine-Driven GHP	EHP
Baltimore	Heating Emissions	585	**393**	462	582
	Cooling Emissions	1,716	2,264	**1,259**	1,458
	Total Emissions	2,301	2,657	**1,720**	2,040
Houston	Heating Emissions	347	**224**	249	277
	Cooling Emissions	2,521	3,647	**2,053**	2,144
	Total Emissions	2,869	3,870	**2,302**	2,421
Las Vegas	Heating Emissions	355	**226**	269	293
	Cooling Emissions	2,782	3,863	**2,240**	2,402
	Total Emissions	3,137	4,089	**2,508**	2,695
Minneapolis	Heating Emissions	1,491	**1,149**	1,264	2,509
	Cooling Emissions	1,143	1,191	**646**	970
	Total Emissions	2,633	2,341	**1,910**	3,480

Figure 10 shows a summary of the average emissions reduction of absorption GHPs, engine-driven GHPs and EHPs compared to the incumbent RTU system across all four analysis locations. On average, absorption GHPs are observed to offer the largest emission reduction compared to the incumbent RTU in the heating mode, while engine-driven GHPs offer the highest overall emission reduction.

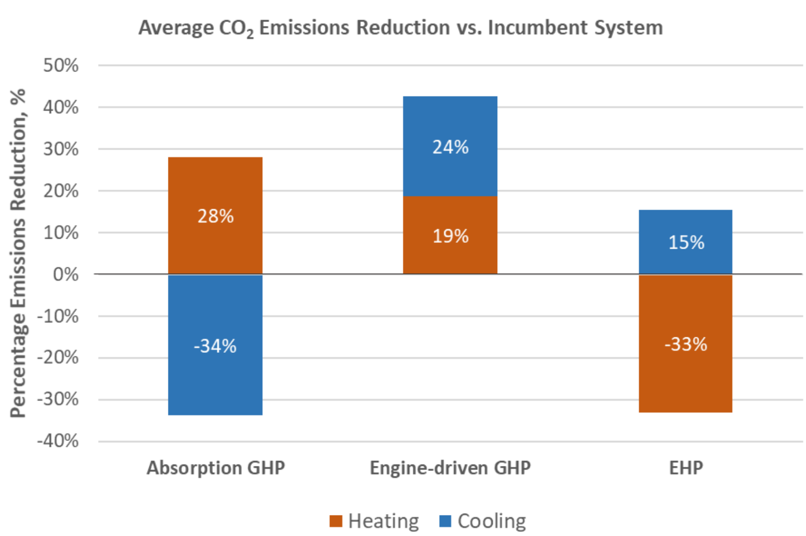


Figure 10: Carbon Emission Percentage Reduction by Heat Pump Technology Compared to Incumbent RTU System

Detailed Analysis Results

ICF modeled the performance of GHP, EHP and the incumbent HVAC system in stand-alone retail stores and medium-sized offices in four analysis locations (totaling eight analysis cases) to estimate the operating costs and emissions of GHPs compared to the incumbent HVAC system and the EHP over a 20-year period. ICF presents detailed results for each of the 8 cases in this section along with explanatory notes and commentary regarding the observed results.

Baltimore, Maryland: Stand-Alone Retail Stores

Year 1 Analysis

ICF estimated the total Year 1 operating costs and emissions for each equipment option for stand-alone retail stores in Baltimore. Table 8 and

Table 9 below show the year 1 operating costs and emissions, respectively, of each technology option for stand-alone retails in Baltimore.

Table 6. Year 1 Operating Cost Estimates for Heating and Cooling at Stand-Alone Retail Stores in Baltimore

Year 1 Operational Cost Estimates		
Heating		
Incumbent System	$8,356	$/year
Engine-driven GHP	$6,661	$/year
Absorption GHP	**$5,627**	**$/year**
EHP	$7,665	$/year
Cooling		
Incumbent System	$7,069	$/year
Engine-driven GHP	**$5,682**	**$/year**
Absorption GHP	$9,961	$/year
EHP	$5,802	$/year

Table 7. Year 1 Emissions Estimates of Heating and Cooling in Stand-Alone Retail Stores in Baltimore

Year 1 CO_2 Emission Estimates		
Heating		
Incumbent System	45	tons
Engine-driven GHP	36	tons
Absorption GHP	**30**	**tons**
EHP	43	tons
Cooling		
Incumbent System	39	tons
Engine-driven GHP	**30**	**tons**
Absorption GHP	53	tons
EHP	32	tons

Note that while absorption GHPs have the lowest operational costs and the lowest emissions for heating, they have the highest costs and the highest emissions associated with cooling. As a result, buildings with low cooling requirements may opt to use absorption GHPs for heating only. Buildings that require similar amounts of heating and cooling could benefit from the well-rounded EHP or engine-driven GHP options.

2021-2040 Projections

ICF applied 2021 commercial electricity and gas rates of 11.69 cents/kWh and 10.91 $/MMBtu, respectively to estimate the total cost of operation of each heat pump option and the incumbent HVAC system in stand-alone retail stores in Baltimore. ICF assumed that electricity and natural gas prices would stay relatively flat on average through the analysis period, only rising with inflation.

To estimate the 20-year cumulative emissions of each technology option in stand-alone retail stores in Baltimore, ICF applied the estimated grid emission rates for the RFCE eGRID region from 2021 to 2040. The RFCE grid emission rates trend from 1,234 lbs/MWh in 2021 to 1,180 lbs/MWh in 2040 (4.4% reduction).[7] ICF also accounted for the effect of increasing RNG penetration in this study by assuming the RNG percentage of total natural gas supply would increase from 0% in 2021 to 13% in 2040.[8]

Figure 11 shows the cumulative 20-year operating costs and emissions of each technology option in stand-alone retail stores in Baltimore.

[7] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[8] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

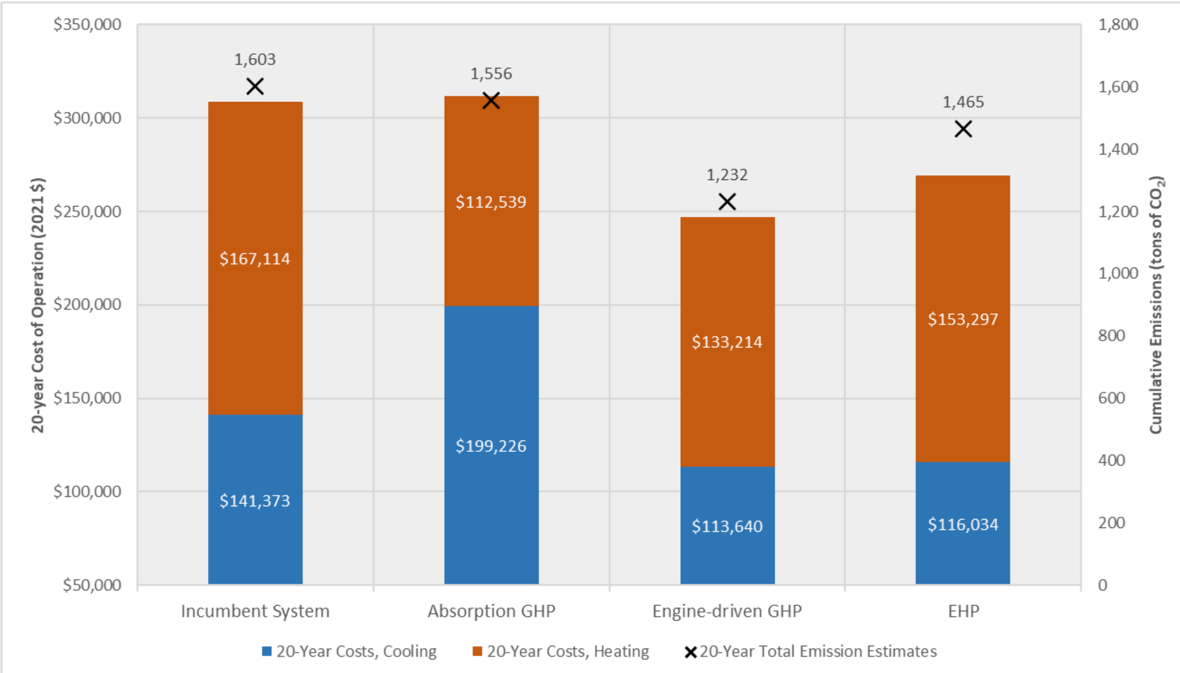


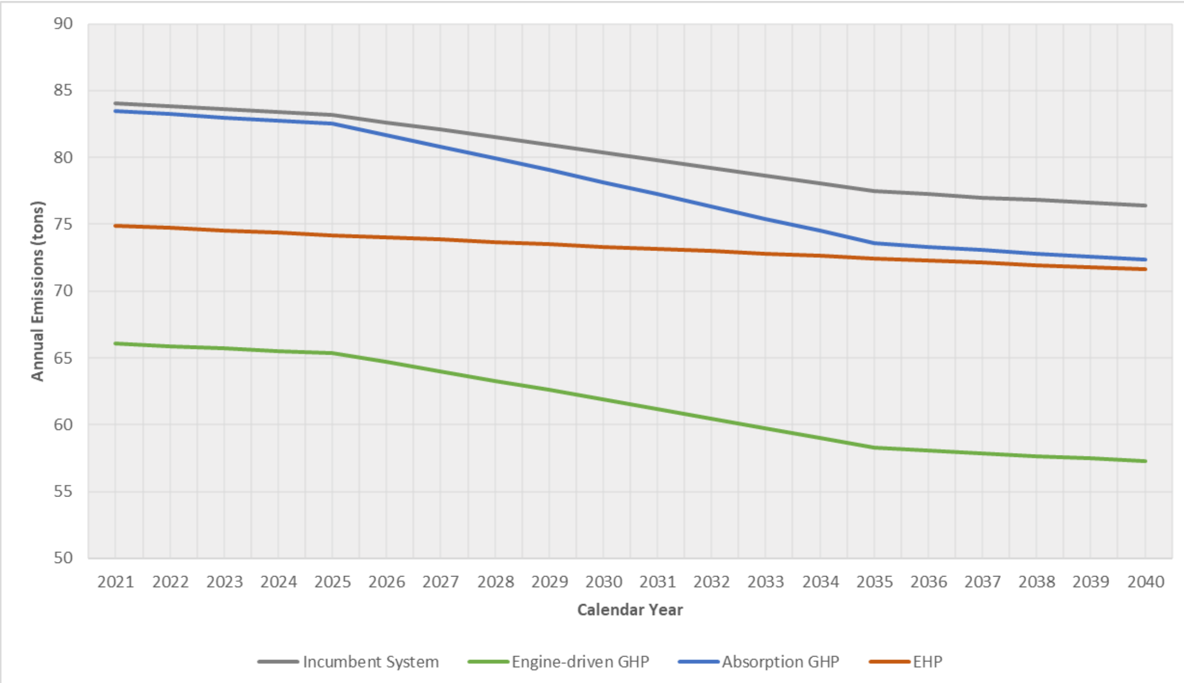
Figure 11. 20-year Operating Costs and Emission Estimates of Heating and Cooling in Stand-Alone Retail Stores in Baltimore

Absorption gas heat pumps have the lowest 20-year heating costs of approximately $112,500, which is 33% lower than the incumbent system and 27% lower than the EHP. Engine-driven GHPs are seen to have the lowest 20-year cooling-only costs and overall costs in retail stores in Baltimore. ICF estimates that in retail stores in Baltimore, the overall 20-year operating cost of engine-driven GHPs are 20% lower than the incumbent system and 8% lower than the EHP. Note that these calculations do not include any effects of summer peak demand reduction. For Baltimore retail stores, GHPs were estimated to reduce peak summer demand by 47%. EHPs – with higher efficiencies than incumbent systems – were estimated to reduce peak summer demand by 14%.

Figure 11 also shows the 20-year cumulative CO_2 emissions of each technology. Engine-driven GHPs are observed to have the lowest 20-year operating emissions in Baltimore retail stores. The overall emissions of engine GHPs is lower than the incumbent system by 23% and the EHP by 16%. ICF has assessed that the high electricity emission rates in the initial years and the slow rate at which the local electric grid is expected to become carbon-free through 2040 results in significant emission advantages for engine-driven GHPs compared to the incumbent system and EHPs in Baltimore.

Figure 12 shows the estimated annual CO_2 emissions of each technology from 2021 through 2040. The annual emission estimates take into account the progression of grid emission rates through 2040 and also accounts for the increasing penetration of zero-carbon RNG. From the figure below, it is observed that the engine-driven GHP has the lowest operating emissions in all years. In the 2025-2035 period, where the US RNG market is expected to expand significantly, GHP emissions are observed to be declining at a faster rate than EHP emissions.

Figure 12. Estimated Annual Carbon Emissions of Heating and Cooling from 2021-2040 in Stand-Alone Retail Stores in Baltimore



Baltimore, Maryland: Medium Offices

Year 1 Analysis

ICF estimated the total Year 1 operating costs and emissions for each equipment option for medium-sized office buildings in Baltimore. Table 8 and

Table 9 below show the Year 1 operating costs and emissions, respectively, of each technology option for medium-sized offices in Baltimore.

Table 8: Year 1 Operating Cost Estimates of Heating and Cooling in Medium-sized Offices in Baltimore

Year 1 Operational Cost Estimates		
Heating		
Incumbent System	$5,861	$/year
Engine-driven GHP	$4,627	$/year
Absorption GHP	**$3,936**	**$/year**
EHP	$5,347	$/year
Cooling		
Incumbent System	$15,773	$/year
Engine-driven GHP	**$12,609**	**$/year**
Absorption GHP	$22,679	$/year
EHP	$13,403	$/year

Table 9: Year 1 Emissions Estimates of Heating and Cooling in Medium-sized Offices in Baltimore

Year 1 CO_2 Emission Estimates		
Heating		
Incumbent System	31	tons
Engine-driven GHP	25	tons
Absorption GHP	**21**	**tons**
EHP	30	tons
Cooling		
Incumbent System	88	tons
Engine-driven GHP	**68**	**tons**
Absorption GHP	121	tons
EHP	75	tons

Note that while absorption GHPs have the lowest operational costs and the lowest emissions for heating, they have the highest costs and the highest emissions associated with cooling. As a result, buildings with low cooling requirements may opt to use absorption GHPs for heating only. Buildings that require similar amounts of heating and cooling could benefit from the well-rounded EHP or engine-driven GHP options.

2021-2040 Projections

ICF applied 2021 commercial electricity and gas rates of 11.69 cents/kWh and 10.91 $/MMBtu, respectively to estimate the total cost of operation of each heat pump option and the incumbent HVAC system in medium-sized offices in Baltimore. ICF assumed that electricity and natural gas prices would stay relatively flat on average through the analysis period, only rising with inflation.

To estimate the 20-year cumulative emissions of each technology option in medium-sized offices in Baltimore, ICF applied the estimated grid emission rates for the RFCE eGRID region from 2021 to 2040. The RFCE grid emission rates trend from 1,234 lbs/MWh in 2021 to 1,180 lbs/MWh in 2040 (4.4% reduction).[9] ICF also accounted for the effect of increasing RNG penetration in this study by assuming the RNG percentage of total natural gas supply would increase from 0% in 2021 to 13% in 2040.[10]

Figure 13 shows the cumulative 20-year operating costs and emissions of each technology option in medium-sized office buildings in Baltimore.

[9] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[10] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

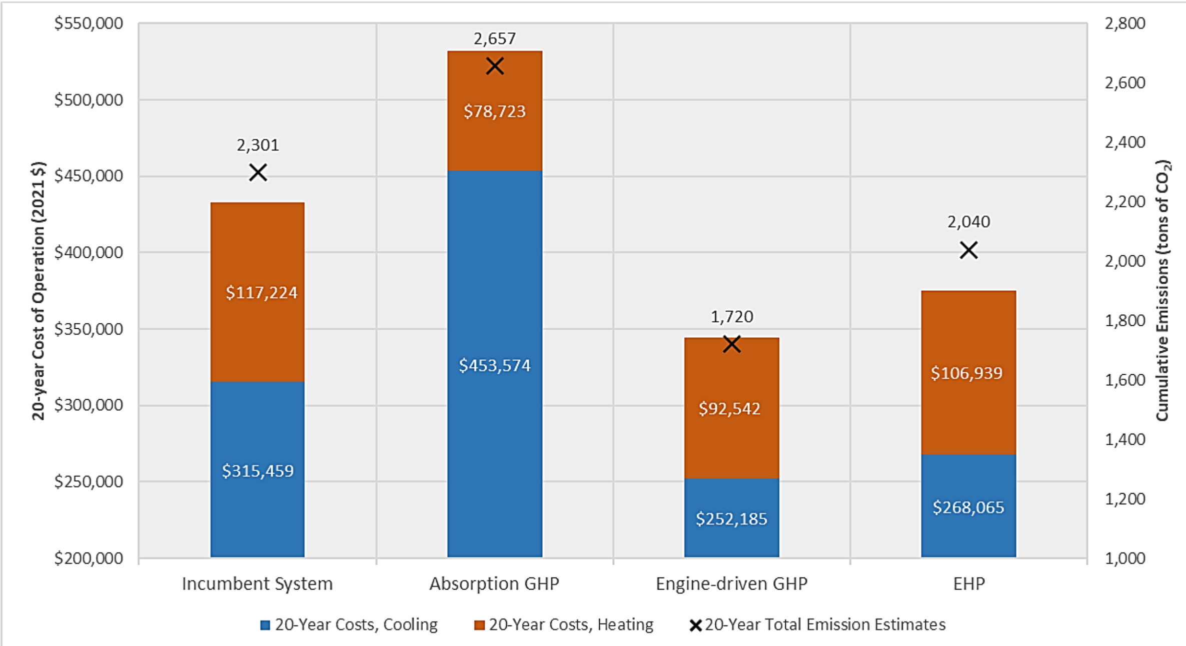


Figure 13: 20-year Operating Costs and Emission Estimates of Heating and Cooling in Medium-sized Offices in Baltimore

Absorption gas heat pumps have the lowest 20-year heating costs of approximately $78,700, which is 33% lower than the incumbent system and 26% lower than the EHP. Engine-driven GHPs are seen to have the lowest 20-year cooling-only costs and overall costs in office buildings in Baltimore. ICF estimates that in medium offices in Baltimore, the overall 20-year operating cost of engine-driven GHPs are 20% lower than the incumbent system and 8% lower than the EHP. Note that these calculations do not include any effects of summer peak demand reduction. For Baltimore offices, GHPs were estimated to reduce peak summer demand by 51%. EHPs – with higher efficiencies than incumbent systems – were estimated to reduce peak summer demand by 11%.

Figure 14 also shows the 20-year cumulative CO_2 emissions of each technology. Engine-driven GHPs are observed to have the lowest 20-year operating emissions in Baltimore offices. The overall emissions of engine GHPs is lower than the incumbent system by 25% and the EHP by 16%. ICF has assessed that the high electricity emission rates in the initial years and the slow rate at which the local electric grid is expected to become carbon-free through 2040 results in significant emission advantages for engine-driven GHPs compared to the incumbent system and EHPs in Baltimore.

Figure 14 shows the estimated annual CO_2 emissions of each technology from 2021 through 2040. From the figure below, it is observed that the engine-driven GHP has the lowest operating emissions in all years. In the 2025-2035 period, where the US RNG market is expected to expand significantly, GHP emissions are observed to be reducing at a faster rate than EHP emissions.

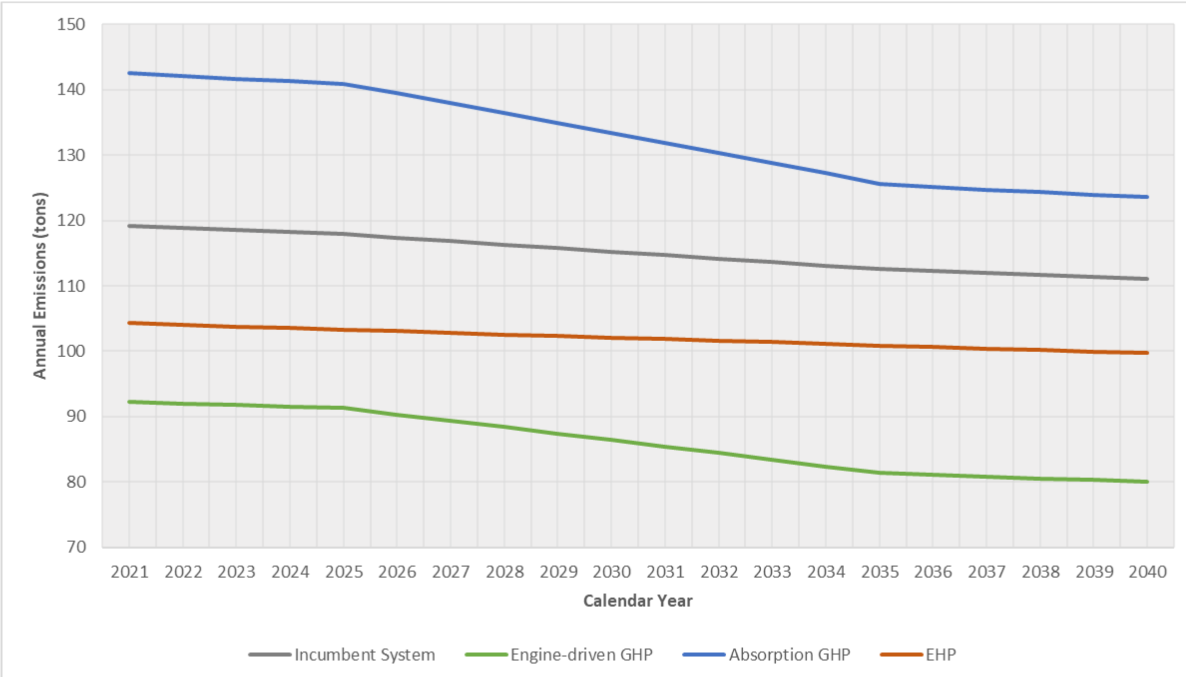


Figure 14: Estimated Annual Carbon Emissions of Heating and Cooling from 2021-2040 in Medium-sized Offices in Baltimore

Houston, Texas: Stand-Alone Retail Stores

Year 1 Analysis

ICF estimated the total Year 1 operating costs and emissions for each equipment option for stand-alone retail stores in Houston. Table 10 and Table 11 below show the Year 1 operating costs and emissions, respectively, of each technology option for stand-alone retail stores in Houston.

Table 10: Year 1 Operating Cost Estimates for Heating and Cooling at Stand-Alone Retail Stores in Houston

Year 1 Operational Cost Estimates		
Heating		
Incumbent System	1,682	$/year
Engine-driven GHP	1,258	$/year
Absorption GHP	**1,103**	**$/year**
EHP	2,237	$/year
Cooling		
Incumbent System	13,614	$/year
Engine-driven GHP	**7,032**	**$/year**
Absorption GHP	12,241	$/year
EHP	11,189	$/year

Table 11: Year 1 Emissions Estimates of Heating and Cooling at Stand-Alone Retail Stores in Houston

Year 1 CO_2 Emission Estimates		
Heating		
Incumbent System	15	tons
Engine-driven GHP	11	tons
Absorption GHP	10	tons
EHP	13	tons
Cooling		
Incumbent System	80	tons
Engine-driven GHP	63	tons
Absorption GHP	111	tons
EHP	66	tons

Low natural gas costs in Texas, combined with strong cooling performance, lead to significant cost advantages for engine-driven GHPs in Houston retail stores. Engine-driven GHPs are also projected to produce the fewest carbon emissions, although EHPs using Texas grid resources are close behind.

2021-2040 Projections

ICF applied 2021 commercial electricity and gas rates of 10.91 cents/kWh and 6.47 $/MMBtu, respectively to estimate the total cost of operation of each heat pump option and the incumbent HVAC system in stand-alone retail stores in Houston. ICF assumed that electricity and natural gas prices would stay relatively flat on average through the analysis period, only rising with inflation.

To estimate the 20-year cumulative emissions of each technology option at stand-alone retail stores in Houston, ICF applied the estimated grid emission rates for the ERCT eGRID region from 2021 to 2040. The ERCT grid emission rates trend from 1,222 lbs/MWh in 2021 to 1,004 lbs/MWh in 2040 (17.8% reduction).[11] ICF also accounted for the effect of increasing RNG penetration in this study by assuming the RNG percentage of total natural gas supply would increase from 0% in 2021 to 13% in 2040.[12]

Figure 15 shows the cumulative 20-year operating costs and emissions of each technology option in stand-alone retail stores in Houston.

[11] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[12] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

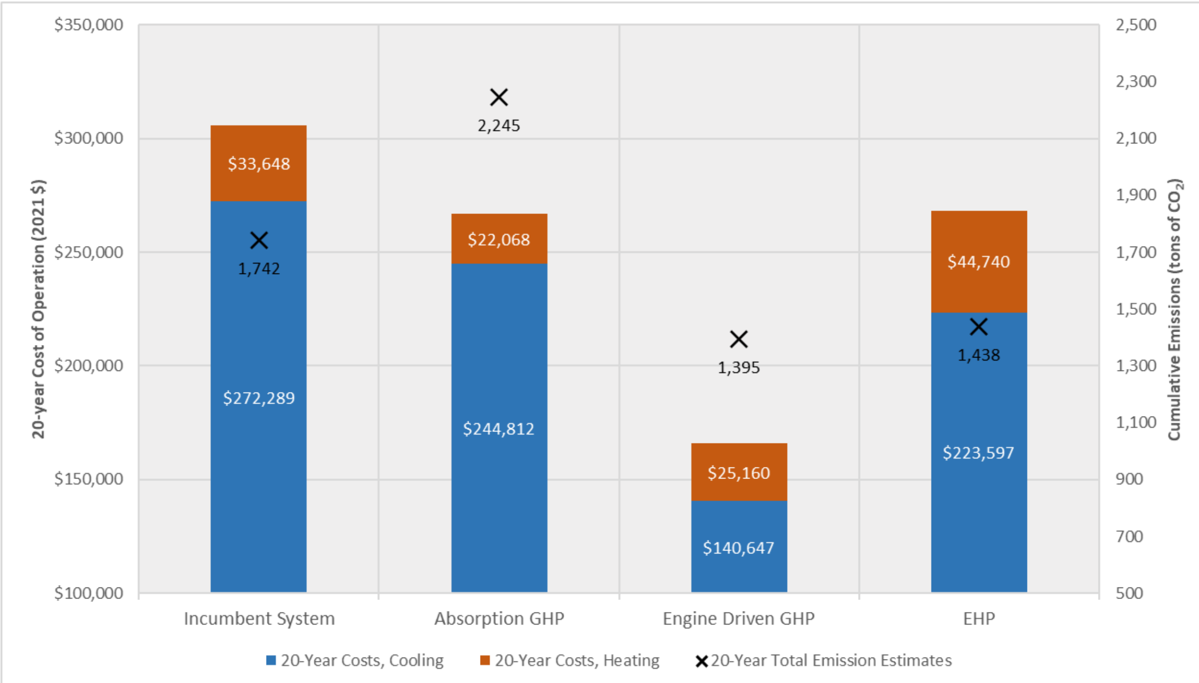


Figure 15: 20-year Operating Costs and Emission Estimates of Heating and Cooling at Stand-Alone Retail Stores in Houston

Absorption gas heat pumps have the lowest 20-year heating costs of approximately $22,000, which is 34% lower than the incumbent system and 50% lower than the EHP. Engine-driven GHPs are seen to have the lowest 20-year cooling-only costs and overall costs in retail stores in Houston. ICF estimates that for stand-alone retail stores in Houston, the overall 20-year operating cost of engine-driven GHPs are 46% lower than the incumbent system and 38% lower than the EHP. Note that these calculations do not include any effects of summer peak demand reduction. For Houston stores, GHPs were estimated to reduce peak summer demand by 49%. EHPs – with higher efficiencies than incumbent systems – were estimated to reduce peak summer demand by 14%.

Figure 15 also shows the 20-year cumulative CO2 emissions of each technology. Engine-driven GHPs are observed to have the lowest 20-year operating emissions in Houston retail stores. The overall emissions of engine GHPs is lower than the incumbent system by 20% and the EHP by 3%. ICF has assessed that the high electricity emission rates in the initial years and the slow rate at which the local electric grid is expected to become carbon-free through 2040 results in significant emission advantages for engine-driven GHPs compared to the incumbent system and EHPs in Houston.

Figure 16 shows the estimated annual CO2 emissions of each technology from 2021 through 2040. The annual emission estimates take into account the progression of grid emission rates through 2040 and also accounts for the increasing penetration of zero-carbon RNG. From the figure below, it is observed that the engine-driven GHP has the lowest operating emissions in all years, although grid emissions associated with EHPs are projected to be lower after 2040.

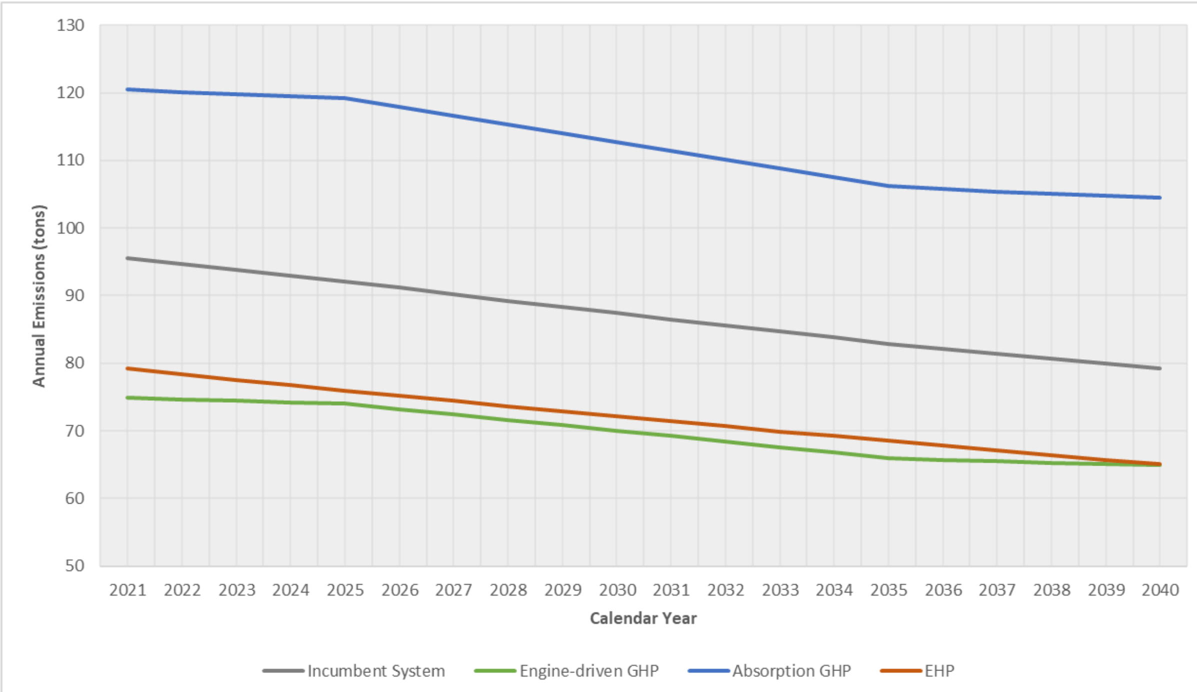


Figure 16: **Estimated Annual Carbon Emissions of Heating and Cooling** from 2021-2040 at Stand-Alone Retail Stores in Houston

Houston, Texas: Medium Offices

Year 1 Analysis

ICF estimated the total Year 1 operating costs and emissions for each equipment option for medium-sized office buildings in Houston. Table 12 and Table 13 below show the Year 1 operating costs and emissions, respectively, of each technology option for medium-sized offices in Houston.

Table 12: Year 1 Operating Cost Estimates for Heating and Cooling at Medium-sized Offices in Houston

Year 1 Operational Cost Estimates		
Heating		
Incumbent System	2,064	$/year
Engine-driven GHP	1,481	$/year
Absorption GHP	1,330	$/year
EHP	2,589	$/year
Cooling		

Incumbent System	23,529	$/year
Engine-driven GHP	12,202	$/year
Absorption GHP	21,670	$/year
EHP	20,004	$/year

Table 13: Year 1 Emissions Estimates of Heating and Cooling at Medium-sized Offices in Houston

Year 1 CO_2 Emission Estimates		
Heating		
Incumbent System	19	tons
Engine-driven GHP	13	tons
Absorption GHP	12	tons
EHP	15	tons
Cooling		
Incumbent System	139	tons
Engine-driven GHP	110	tons
Absorption GHP	196	tons
EHP	118	tons

Low natural gas costs in Texas, combined with strong cooling performance, lead to significant cost advantages for engine-driven GHPs in Houston offices. Engine-driven GHPs are also projected to produce the fewest carbon emissions, although EHPs using Texas grid resources are close behind.

2021-2040 Projections

ICF applied 2021 commercial electricity and gas rates of 10.91 cents/kWh and 6.47 $/MMBtu, respectively to estimate the total cost of operation of each heat pump option and the incumbent HVAC system in medium-sized offices in Houston. ICF assumed that electricity and natural gas prices would stay relatively flat on average through the analysis period, only rising with inflation.

To estimate the 20-year cumulative emissions of each technology option in medium-sized offices in Houston, ICF applied the estimated grid emission rates for the ERCT eGRID region from 2021 to 2040. The ERCT grid emission rates trend from 1,222 lbs/MWh in 2021 to 1,004 lbs/MWh in 2040 (17.8% reduction).[13] ICF also accounted for the effect of increasing RNG penetration in this study by assuming the RNG percentage of total natural gas supply would increase from 0% in 2021 to 13% in 2040.[14]

Figure 17 shows the cumulative 20-year operating costs and emissions of each technology option in medium-sized office buildings in Houston.

[13] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[14] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

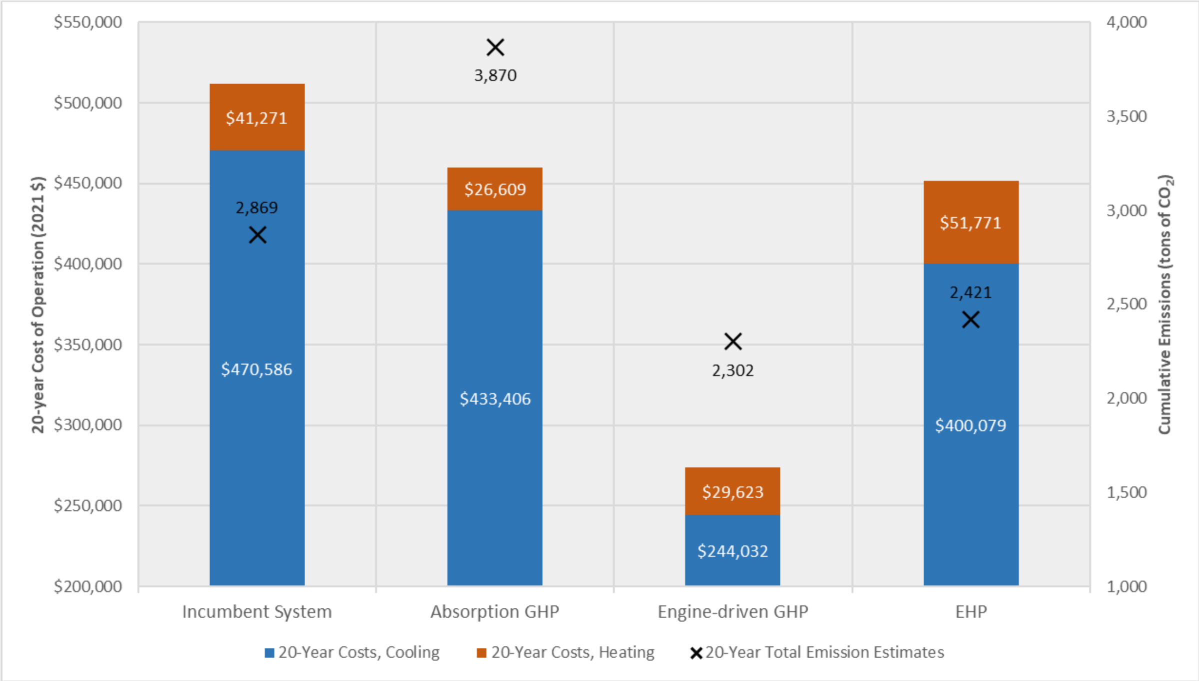


Figure 17: Estimated Annual Carbon Emissions of Heating and Cooling at Medium-sized Offices in Houston

Absorption gas heat pumps have the lowest 20-year heating costs of approximately $26,600 which is 36% lower than the incumbent system and 49%lower than the EHP. Engine-driven GHPs are seen to have the lowest 20-year cooling-only costs and overall costs in office buildings in Houston. ICF estimates that in medium-sized offices in Houston, the overall 20-year operating cost of engine-driven GHPs are 47% lower than the incumbent system and 40% lower than the EHP. Note that these calculations do not include any effects of summer peak demand reduction. For Houston offices, GHPs were estimated to reduce peak summer demand by 51%. EHPs – with higher efficiencies than incumbent systems – were estimated to reduce peak summer demand by 11%.

Figure 17 also shows the 20-year cumulative CO_2 emissions of each technology. Engine-driven GHPs are observed to have the lowest 20-year operating emissions in Houston offices. The overall emissions of engine GHPs is lower than the incumbent system by 20% and the EHP by 5%. ICF has assessed that the high electricity emission rates in the initial years and the slow rate at which the local electric grid is expected to become carbon-free through 2040 results in significant emission advantages for engine-driven GHPs compared to the incumbent system and EHPs in Houston.

Figure 18 shows the estimated annual CO_2 emissions of each technology from 2021 through 2040. The annual emission estimates take into account the progression of grid emission rates through 2040 and also accounts for the increasing penetration of zero-carbon RNG. From the figure below, it is observed that the engine-driven GHP has the lowest operating emissions in all years.

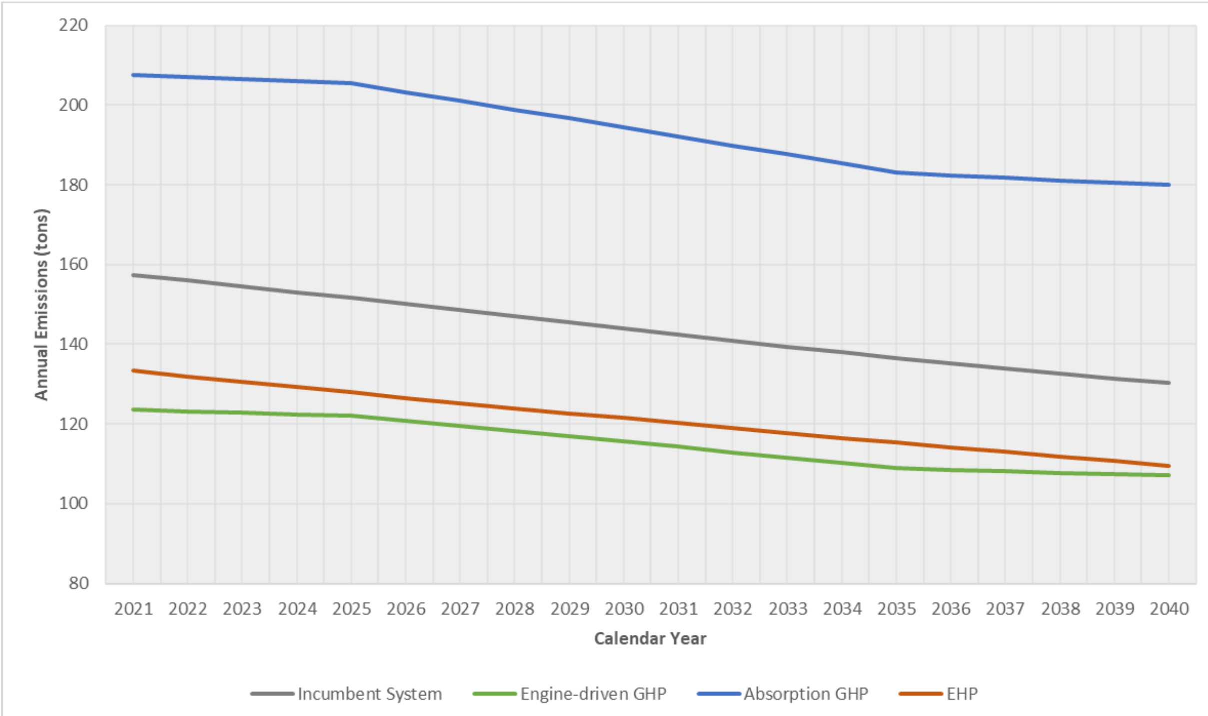


Figure 18: Estimated Annual Carbon Emissions of Heating and Cooling from 2021-2040 in Medium-sized Offices in Houston

Las Vegas, Nevada: Stand-Alone Retail Stores

Year 1 Analysis

ICF estimated the total Year 1 operating costs and emissions for each equipment option for stand-alone retail stores in Las Vegas. Table 14 and Table 15 below show the Year 1 operating costs and emissions, respectively, of each technology option for stand-alone retail stores in Las Vegas.

Table 14: Year 1 Operating Cost Estimates for Heating and Cooling at Stand-Alone Retail Stores in Las Vegas

Year 1 Operational Cost Estimates		
Heating		
Incumbent System	2,293	$/year
Engine-driven GHP	1,767	$/year
Absorption GHP	1,468	$/year
EHP	2,015	$/year
Cooling		
Incumbent System	9,317	$/year
Engine-driven GHP	7,172	$/year
Absorption GHP	12,242	$/year
EHP	7,803	$/year

Table 15: Year 1 Emissions Estimates of Heating and Cooling at Stand-Alone Retail Stores in Las Vegas

Year 1 CO_2 Emission Estimates		
Heating		
Incumbent System	18	tons

Engine-driven GHP	14	tons
Absorption GHP	12	tons
EHP	17	tons
Cooling		
Incumbent System	80	tons
Engine-driven GHP	57	tons
Absorption GHP	97	tons
EHP	67	tons

Cooling requirements far outweigh heating requirements for Las Vegas retail stores, making strong cooling performance a prerequisite for favorable heat pump economics and emissions. Engine-driven GHPs were shown to operate at the lowest cost and produce the fewest emissions, followed closely by EHPs.

2021-2040 Projections

ICF applied 2021 commercial electricity and gas rates of 9.18 cents/kWh and 7.40 $/MMBtu, respectively to estimate the total cost of operation of each heat pump option and the incumbent HVAC system at stand-alone retail stores in Las Vegas. ICF assumed that electricity and natural gas prices would stay relatively flat on average through the analysis period, only rising with inflation.

To estimate the 20-year cumulative emissions of each technology option at stand-alone retail stores in the Las Vegas area, ICF applied the estimated grid emission rates for the NWPP eGRID region from 2021 to 2040. The NWPP grid emission rates trend from 1,487 lbs/MWh in 2021 to 977 lbs/MWh in 2040 (34.3% reduction).[15] ICF also accounted for the effect of increasing RNG penetration in this study by assuming the RNG percentage of total natural gas supply would increase from 0% in 2021 to 13% in 2040.[16]

Figure 19 shows the cumulative 20-year operating costs and emissions of each technology option at stand-alone retail stores in Las Vegas.

[15] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[16] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

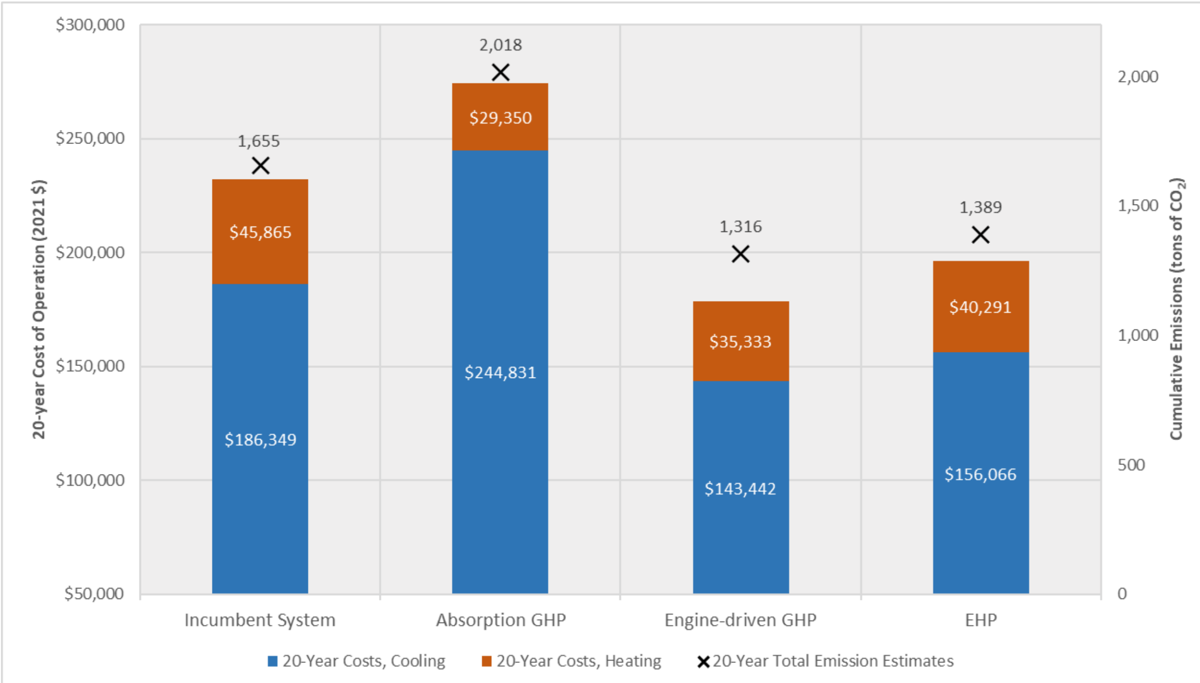


Figure 19: 20-year Operating Costs and Emission Estimates of GHPs at Stand-Alone Retail Stores in Las Vegas

Absorption gas heat pumps have the lowest 20-year heating costs of approximately $29,400, which is 36% lower than the incumbent system and 17% lower than the EHP. Engine-driven GHPs are seen to have the lowest 20-year cooling-only costs and overall costs at stand-alone retail stores in the Las Vegas area. ICF estimates that at stand-alone retail stores in Las Vegas, the overall 20-year operating cost of engine-driven GHPs are 23% lower than the incumbent system and 9% lower than the EHP. Note that these calculations do not include any effects of summer peak demand reduction. For Las Vegas stores, GHPs were estimated to reduce peak summer demand by 47%. EHPs – with higher efficiencies than incumbent systems – were estimated to reduce peak summer demand by 9%.

Figure 19 also shows the 20-year cumulative CO2 emissions of each technology. Engine-driven GHPs are observed to have the lowest 20-year operating emissions in Las Vegas retail stores. The overall emissions of engine GHPs is lower than the incumbent system by 20% and the EHP by 5%. ICF has assessed that the high electricity emission rates in the initial years and the slow rate at which the local electric grid is expected to become carbon-free through 2040 results in significant emission advantages for engine-driven GHPs compared to the incumbent system and EHPs in Las Vegas.

Figure 20 shows the estimated annual CO_2 emissions of each technology from 2021 through 2040. The annual emission estimates take into account the progression of grid emission rates through 2040 and also accounts for the increasing penetration of zero-carbon RNG. From the figure below, it is observed that the engine-driven GHP has the lowest operating emissions before 2036, with the cleaner grid producing lower carbon emissions for EHP after this time.

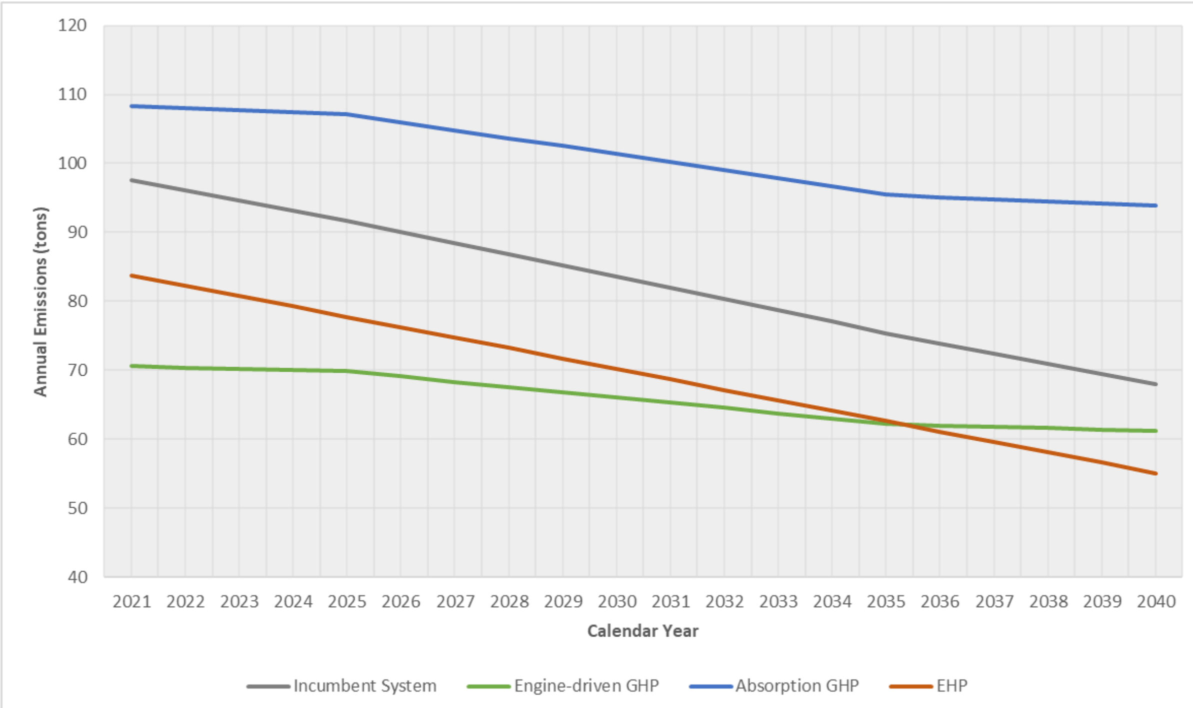


Figure 20: Estimated Annual Carbon Emissions of Cooling and Heating from 2021-2040 at Stand-Alone Retail Stores in Las Vegas

Las Vegas, Nevada: Medium Offices

Year 1 Analysis

ICF estimated the total Year 1 operating costs and emissions for each equipment option for medium-sized office buildings in Las Vegas. Table 16 and Table 17 below show the Year 1 operating costs and emissions, respectively, of each technology option for medium-sized offices in Las Vegas.

Table 16: Year 1 Operating Cost Estimates for Heating and Cooling at Medium-sized Offices in Las Vegas

Year 1 Operational Cost Estimates		
Heating		
Incumbent System	2,414	$/year
Engine-driven GHP	1,826	$/year
Absorption GHP	1,532	$/year
EHP	2,073	$/year
Cooling		
Incumbent System	19,668	$/year
Engine-driven GHP	15,213	$/year
Absorption GHP	26,240	$/year
EHP	16,984	$/year

Table 17: Year 1 Emissions Estimates of Heating and Cooling at Medium-sized Offices in Las Vegas

Year 1 CO_2 Emission Estimates		
Heating		
Incumbent System	19	tons
Engine-driven GHP	14	tons
Absorption GHP	12	tons
EHP	18	tons
Cooling		
Incumbent System	168	tons
Engine-driven GHP	120	tons
Absorption GHP	207	tons
EHP	145	tons

Cooling requirements far outweigh heating requirements for Las Vegas office buildings, making strong cooling performance a prerequisite for favorable heat pump economics and emissions. Engine-driven GHPs were shown to operate at the lowest cost and produce the fewest emissions, followed closely by EHPs.

2021-2040 Projections

ICF applied 2021 commercial electricity and gas rates of 9.18 cents/kWh and 7.40 $/MMBtu, respectively to estimate the total cost of operation of each heat pump option and the incumbent HVAC system in medium-sized offices in Las Vegas. ICF assumed that electricity and natural gas prices would stay relatively flat on average through the analysis period, only rising with inflation.

To estimate the 20-year cumulative emissions of each technology option in medium-sized offices in Las Vegas, ICF applied the estimated grid emission rates for the NWPP eGRID region from 2021 to 2040. The NWPP grid emission rates trend from 1,487 lbs/MWh in 2021 to 977 lbs/MWh in 2040 (34.3% reduction).[17] ICF also accounted for the effect of increasing RNG penetration in this study by assuming the RNG percentage of total natural gas supply would increase from 0% in 2021 to 13% in 2040.[18]

Figure 21 shows the cumulative 20-year operating costs and emissions of each technology option in medium-sized office buildings in Las Vegas.

[17] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf
[18] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

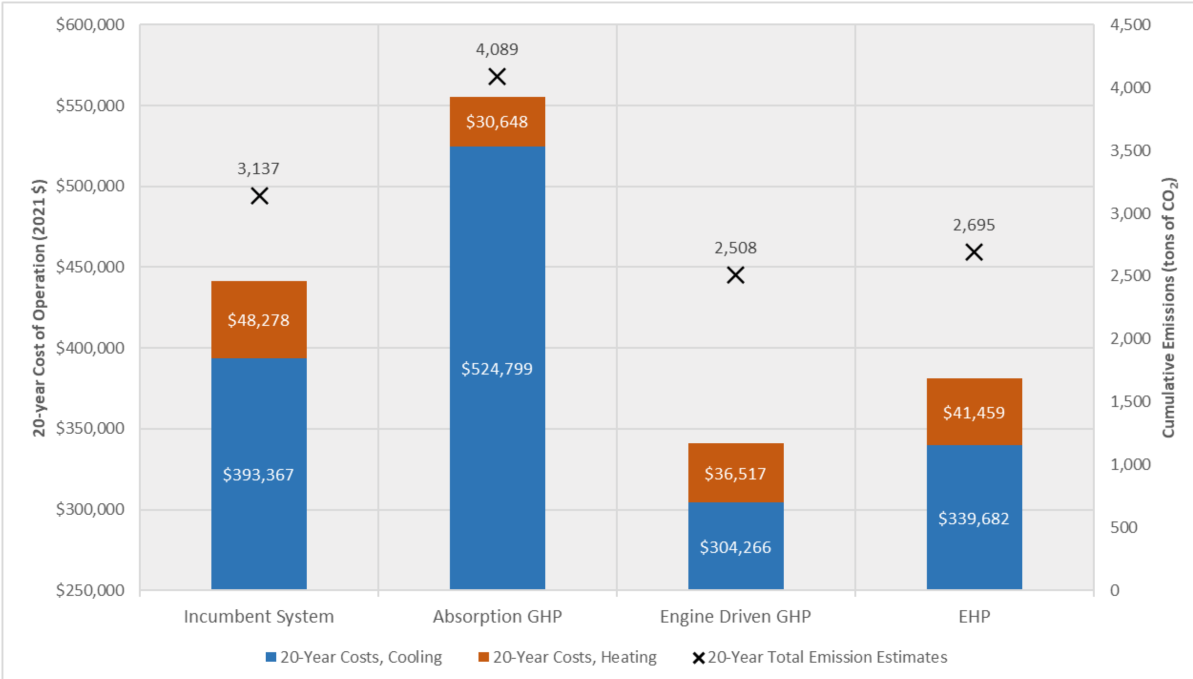


Figure 21: 20-year Operating Costs and Emission Estimates of Heating and Cooling at Medium-sized Offices in Las Vegas

Absorption gas heat pumps have the lowest 20-year heating costs of approximately $30,600, which is 24% lower than the incumbent system and 12% lower than the EHP. Engine-driven GHPs are seen to have the lowest 20-year cooling-only costs and overall costs in office buildings in Las Vegas. ICF estimates that in medium-sized offices in Las Vegas, the overall 20-year operating cost of engine-driven GHPs are 23% lower than the incumbent system and 11% lower than the EHP. Note that these calculations do not include any effects of summer peak demand reduction. For Las Vegas offices, GHPs were estimated to reduce peak summer demand by 56%. EHPs – with higher efficiencies than incumbent systems – were estimated to reduce peak summer demand by 6%.

Figure 21 also shows the 20-year cumulative CO_2 emissions of each technology. Engine-driven GHPs are observed to have the lowest 20-year operating emissions in Baltimore offices. The overall emissions of engine GHPs is lower than the incumbent system by 20% and the EHP by 7%. ICF has assessed that the high electricity emission rates in the initial years and the slow rate at which the local electric grid is expected to become carbon-free through 2040 results in significant emission advantages for engine-driven GHPs compared to the incumbent system and EHPs in Las Vegas.

Figure 22 shows the estimated annual CO_2 emissions of each technology from 2021 through 2040. The annual emission estimates take into account the progression of grid emission rates through 2040 and also accounts for the increasing penetration of zero-carbon RNG. From the figure below, it is observed that the engine-driven GHP has the lowest operating emissions before 2036, with a cleaner grid producing lower carbon emissions for the EHP after this time.

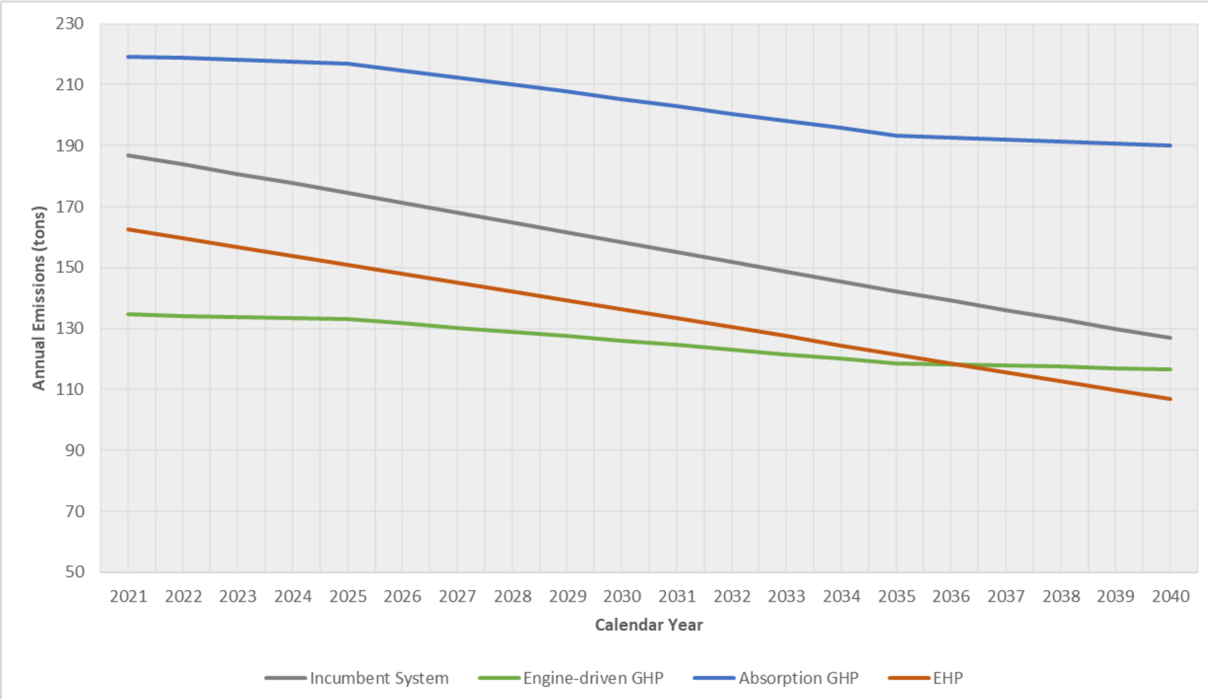


Figure 22: Estimated Annual Carbon Emissions of Heating and Cooling from 2021-2040 at Medium-sized Offices in Las Vegas

Minneapolis, Minnesota: Stand-Alone Retail Stores

Year 1 Analysis

ICF estimated the total Year 1 operating costs and emissions for each equipment option for stand-alone retail stores in Minneapolis. Table 18 and Table 19 below show the year 1 operating costs and emissions, respectively, of each technology option for stand-alone retail stores in Minneapolis.

Table 18: Year 1 Operating Cost Estimates for Heating and Cooling at Stand-Alone Retail Stores in Minneapolis

Year 1 Operational Cost Estimates		
Heating		
Incumbent System	11,033	$/year
Engine-driven GHP	9,361	$/year
Absorption GHP	8,482	$/year
EHP	19,979	$/year
Cooling		
Incumbent System	3,227	$/year
Engine-driven GHP	1,686	$/year
Absorption GHP	3,040	$/year
EHP	2,647	$/year

Table 19: Year 1 Emissions Estimates of Heating and Cooling at Stand-Alone Retail Stores in Minneapolis

Year 1 CO_2 Emission Estimates		
Heating		
Incumbent System	95	tons
Engine-driven GHP	81	tons
Absorption GHP	73	tons
EHP	167	tons
Cooling		
Incumbent System	27	tons
Engine-driven GHP	15	tons
Absorption GHP	26	tons
EHP	22	tons

Heating requirements for retail stores far outweigh cooling requirements in Minneapolis. Absorption GHPs offer the strongest performance for heating for Minneapolis retail stores, followed by engine-driven GHPs. For stores that do not require significant amounts of cooling, absorption GHPs may be the most favorable option. For buildings with more cooling requirements, the engine-driven GHP is likely to be the most favorable.

2021-2040 Projections

ICF applied 2021 commercial electricity and gas rates of 10.72 cents/kWh and 6.77 $/MMBtu, respectively to estimate the total cost of operation of each heat pump option and the incumbent HVAC system in stand-alone retail stores in Minneapolis. ICF assumed that electricity and natural gas prices would stay relatively flat on average through the analysis period, only rising with inflation.

To estimate the 20-year cumulative emissions of each technology option in stand-alone retail stores in Minneapolis, ICF applied the estimated grid emission rates for the MROW eGRID region from 2021 to 2040. The MROW grid emission rates trend from 1,700 lbs/MWh in 2021 to 1,343 lbs/MWh in 2040 (21.0% reduction).[19] ICF also accounted for the effect of increasing RNG penetration in this study by assuming the RNG percentage of total natural gas supply would increase from 0% in 2021 to 13% in 2040.[20]

Figure 23 shows the cumulative 20-year operating costs and emissions of each technology option at stand-alone retail stores in Minneapolis.

[19] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[20] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

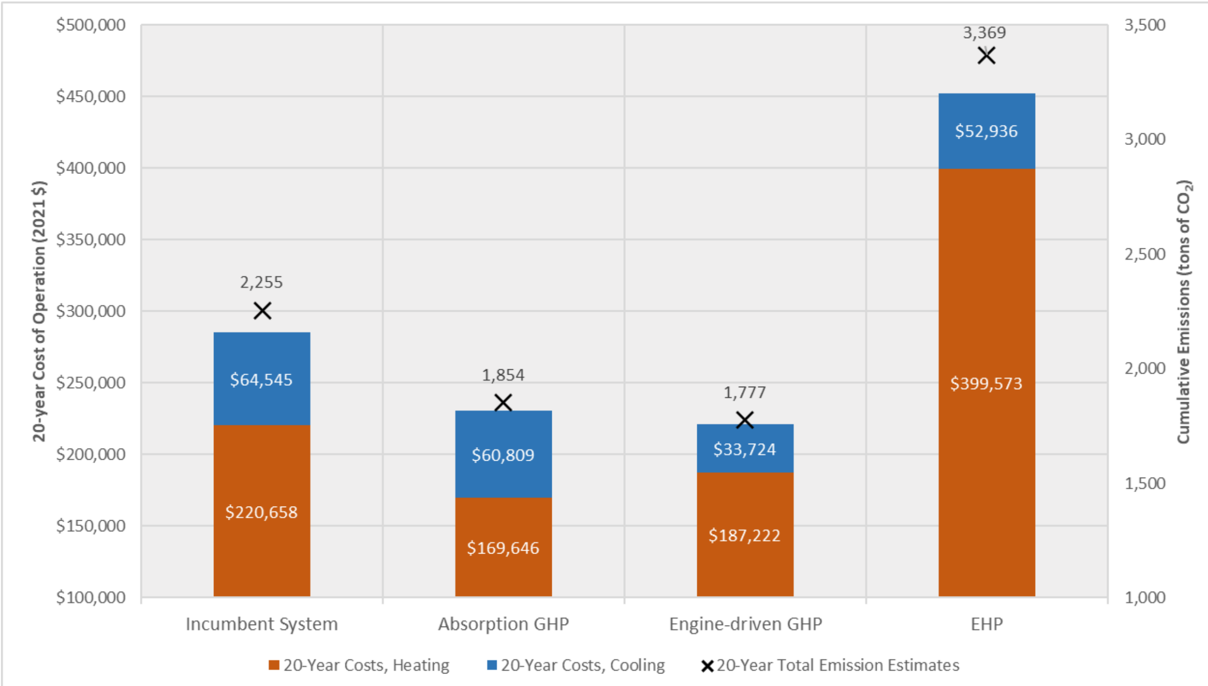


Figure 23: 20-year Operating Costs and Emission Estimates of Heating and Cooling at Stand-Alone Retail Stores in Minneapolis

Absorption gas heat pumps have the lowest 20-year heating costs of $169,646, which is 23% lower than the incumbent system and 58% lower than the EHP. Engine-driven GHPs are seen to have the lowest 20-year cooling-only costs and overall costs at retail stores in Minneapolis. ICF estimates that in retails stores in Minneapolis, the overall 20-year operating cost of engine-driven GHPs are 23% lower than the incumbent system and 51% lower than the EHP. Note that these calculations do not include any effects of summer peak demand reduction. For Minneapolis stores, GHPs were estimated to reduce peak summer demand by 38%. EHPs – with higher efficiencies than incumbent systems – were estimated to reduce peak summer demand by 18%.

Figure 23 also shows the 20-year cumulative CO_2 emissions of each technology. Engine-driven GHPs are observed to have the lowest 20-year operating emissions at Minneapolis retail stores. The overall emissions of engine GHPs is lower than the incumbent system by 21% and the EHP by 47%. ICF has assessed that the high electricity emission rates in the initial years and the slow rate at which the local electric grid is expected to become carbon-free through 2040 results in significant emission advantages for engine-driven GHPs compared to the incumbent system and EHPs in Minneapolis.

Figure 24 shows the estimated annual CO_2 emissions of each technology from 2021 through 2040. The annual emission estimates take into account the progression of grid emission rates through 2040 and also accounts for the increasing penetration of zero-carbon RNG. From the figure below, it is observed that the engine-driven GHP has the lowest operating emissions in all years.

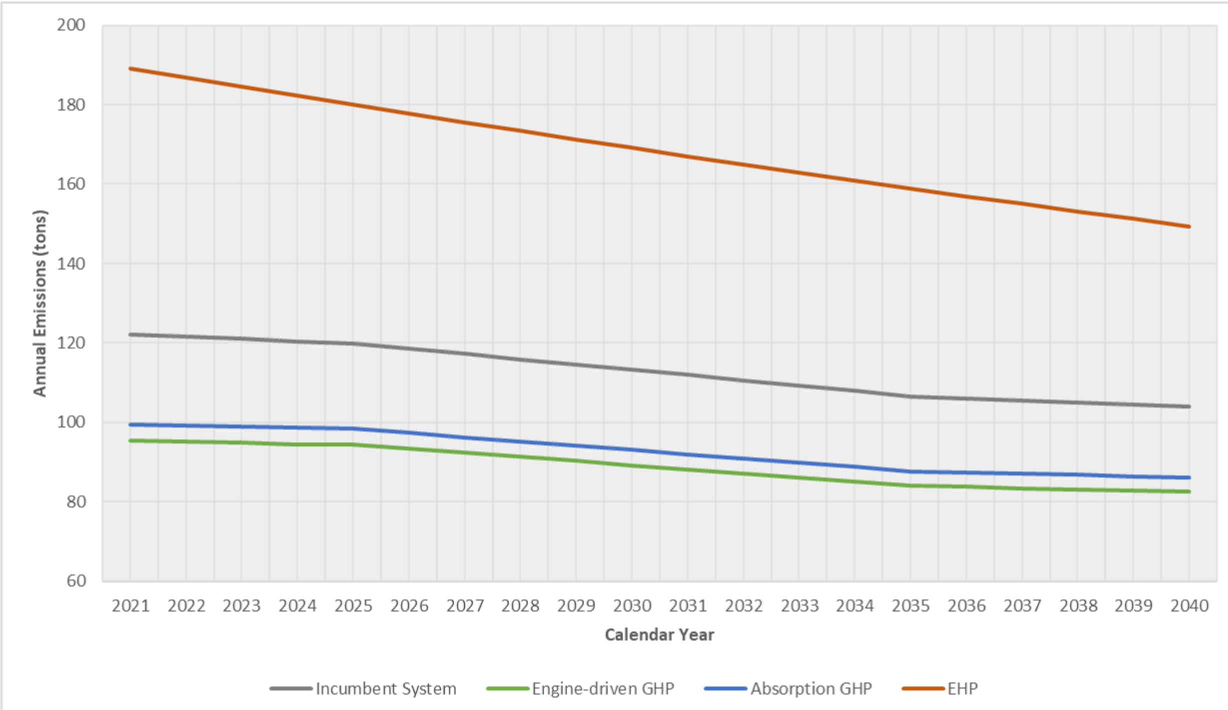


Figure 24: Estimated Annual Carbon Emissions of Heating and Cooling from 2021-2040 at Stand-Alone Retail Stores in Minneapolis

Minneapolis, Minnesota: Medium Offices

Year 1 Analysis

ICF estimated the total Year 1 operating costs and emissions for each equipment option for medium-sized office buildings in Minneapolis. Table 20 and Table 21 below show the Year 1 operating costs and emissions, respectively, of each technology option for medium-sized offices in Minneapolis.

Table 20: Year 1 Operating Cost Estimates for Heating and Cooling at Medium-sized Offices in Minneapolis

Year 1 Operational Cost Estimates		
Heating		
Incumbent System	9,268	$/year
Engine-driven GHP	7,856	$/year
Absorption GHP	7,144	$/year
EHP	16,850	$/year
Cooling		
Incumbent System	7,672	$/year
Engine-driven GHP	4,018	$/year
Absorption GHP	7,406	$/year
EHP	6,516	$/year

Table 21: Year 1 Emissions Estimates of Heating and Cooling at Medium-sized Offices in Minneapolis

Year 1 CO_2 Emission Estimates		
Heating		
Incumbent System	80	tons
Engine-driven GHP	68	tons
Absorption GHP	62	tons
EHP	141	tons
Cooling		
Incumbent System	64	tons
Engine-driven GHP	35	tons
Absorption GHP	64	tons
EHP	54	tons

Heating requirements for commercial offices outweigh cooling requirements in Minneapolis. Absorption GHPs offer the strongest performance for heating Minneapolis office buildings, followed by engine-driven GHPs. For buildings that do not require significant amounts of cooling, absorption GHPs may be the most favorable option. For buildings with more cooling requirements, the engine-driven GHP is likely to be the most favorable.

2021-2040 Projections

ICF applied 2021 commercial electricity and gas rates of 10.72 cents/kWh and 6.77 $/MMBtu, respectively to estimate the total cost of operation of each heat pump option and the incumbent HVAC system in medium-sized offices in Minneapolis. ICF assumed that electricity and natural gas prices would stay relatively flat on average through the analysis period, only rising with inflation.

To estimate the 20-year cumulative emissions of each technology option in medium-sized offices in Minneapolis, ICF applied the estimated grid emission rates for the MROW eGRID region from 2021 to 2040. The MROW grid emission rates trend from 1,700 lbs/MWh in 2021 to 1,343 lbs/MWh in 2040 (21.0% reduction).[21] ICF also accounted for the effect of increasing RNG penetration in this study by assuming the RNG percentage of total natural gas supply would increase from 0% in 2021 to 13% in 2040.[22]

Figure 25 shows the cumulative 20-year operating costs and emissions of each technology option in medium-sized office buildings in Minneapolis.

[21] Combined Heat and Power Potential for Carbon Emission Reductions, National Assessment 2020-2050, Prepared by ICF for Energy Solutions Center, 2020, https://consortia.myescenter.com/CHP/ESC_CHP_Emissions-Full_Study-ICF-071320.pdf

[22] American Gas Foundation, Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

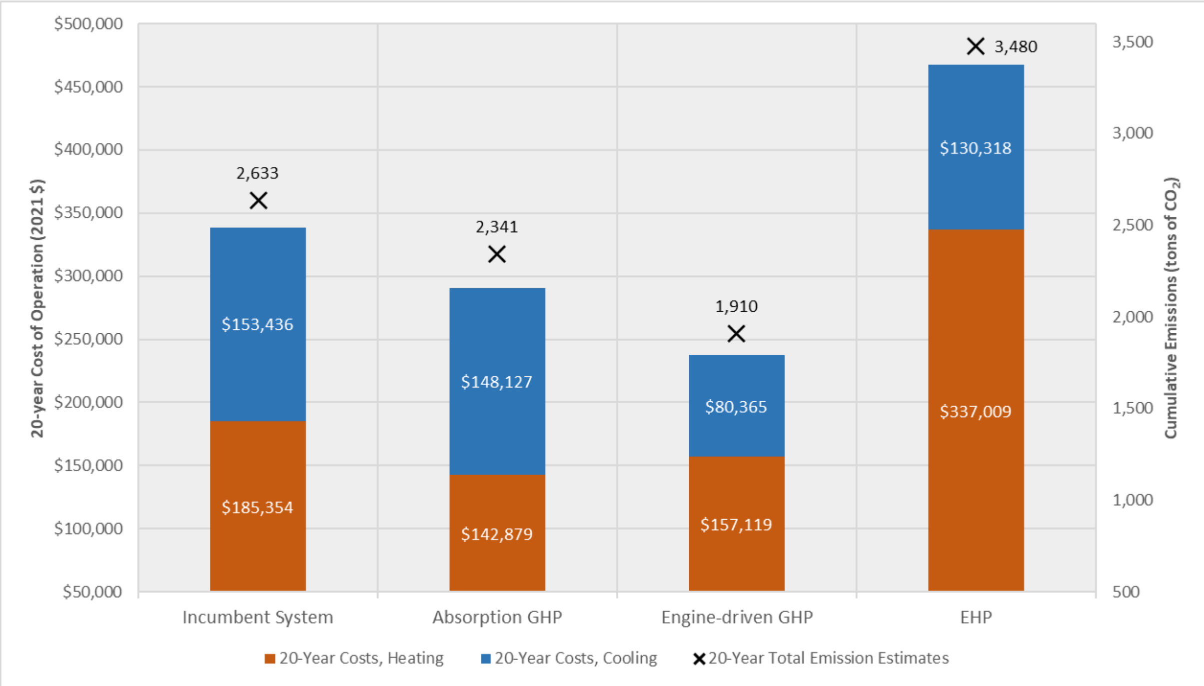


Figure 25: 20-year Operating Costs and Emission Estimates of Heating and Cooling in Medium-sized Offices at Minneapolis

Absorption gas heat pumps have the lowest 20-year heating costs of approximately $142,879, which is 15% lower than the incumbent system and 53% lower than the EHP. Engine-driven GHPs are seen to have the lowest 20-year cooling-only costs and overall costs in office buildings in Minneapolis. ICF estimates that in medium-sized offices in Minneapolis, the overall 20-year operating cost of engine-driven GHPs are 30% lower than the incumbent system and 50% lower than the EHP. Note that these calculations do not include any effects of summer peak demand reduction. For Minneapolis offices, GHPs were estimated to reduce peak summer demand by 42%. EHPs – with higher efficiencies than incumbent systems – were estimated to reduce peak summer demand by 15%.

Figure 25 also shows the 20-year cumulative CO_2 emissions of each technology. Engine-driven GHPs are observed to have the lowest 20-year operating emissions in Minneapolis offices. The overall emissions of engine GHPs is lower than the incumbent system by 27% and the EHP by 45%. ICF has assessed that the high electricity emission rates in the initial years and the slow rate at which the local electric grid is expected to become carbon-free through 2040 results in significant emission advantages for engine-driven GHPs compared to the incumbent system and EHPs in Minneapolis.

Figure 26 shows the estimated annual CO_2 emissions of each technology from 2021 through 2040. The annual emission estimates take into account the progression of grid emission rates through 2040 and also accounts for the increasing penetration of zero-carbon RNG. From the figure below, it is observed that the engine-driven GHP has the lowest operating emissions in all years.

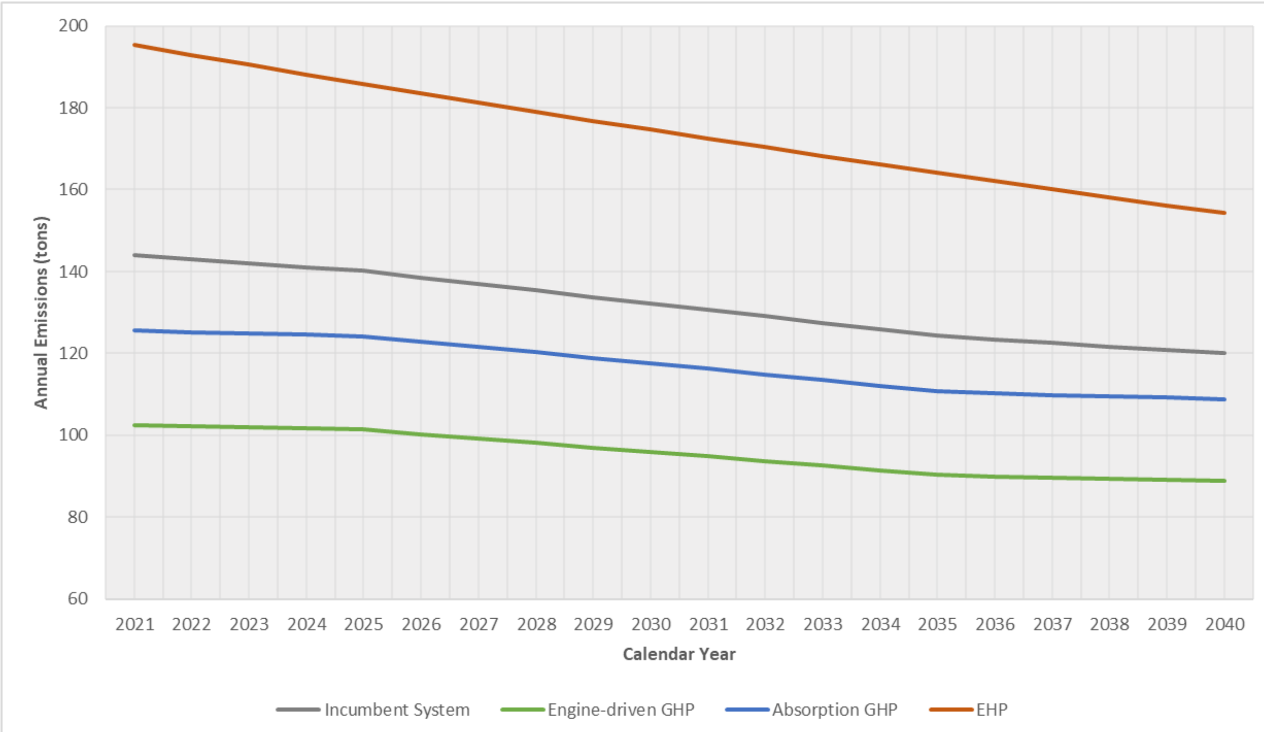


Figure 26: Estimated Annual Carbon Emissions of Heating and Cooling from 2021-2040 at Medium-sized Offices in Minneapolis

V. Conclusions

This study demonstrated that heat pump technologies driven by both gas and electricity can reduce emissions and energy costs compared to incumbent heating and cooling technologies at commercial buildings. Absorption GHPs tended to perform best in heating mode, with high heating efficiencies leading to low costs and emissions. Engine-driven GHPs performed most favorably all around, with the lowest costs and emissions for cooling and as an overall system. Electric heat pumps had slightly higher costs and emissions in most locations. However, in Minnesota the EHP was hampered by poor cold weather performance, falling behind both GHP options along with the incumbent system.

EHPs have the highest on-site efficiencies, with coefficients of performance sometimes three times as high as GHPs. However, EHPs require electricity delivered from power plants, usually produced by fossil fuels with conversion efficiencies under 40 percent. When combined with grid transmission and distribution losses, the effective efficiencies of EHPs are often comparable to GHPs.

The results of the analysis showed that gas heat pumps offered the lowest-cost option producing the lowest total emissions over the 20-year period in each of the evaluated locations. The modeled EHPs came close to the engine-driven GHPs, but higher electricity costs and relatively high marginal grid emissions over the analysis period prevented EHPs from achieving the lowest costs or emissions.

Decarbonization policies and programs have often focused on the deployment of EHPs as a strategy to reduce emissions from commercial and residential buildings. However, the marginal grid resources used to power EHPs are often fossil fuel resources, thus reducing EHPs' emissions benefits. As such, GHPs may have improved emission reductions for certain buildings and climates compared to EHPs.

The potential for EHPs to reduce emissions will increase as the electricity grid incorporates greater levels of low and zero-carbon electricity resources. Despite this, the study demonstrated that GHPs will continue to provide better emission reductions than EHPs with further emissions improvements as greater levels of renewable natural gas and zero-carbon hydrogen are introduced into the gas distribution system

Both EHPs and GHPs can play a strong role in decarbonizing commercial buildings. Policymakers should consider the merits of incentivizing efficient GHPs for carbon emission reductions, especially in areas with cold climates and existing gas infrastructure. The carbon emissions benefits could exceed those of EHPs and are likely to do so for some time in locations where fossil fuels continue to be used by grid operators on the margin. These factors should be taken into consideration as policymakers develop regional, state, and local decarbonization policies and programs.

Appendix A. Detailed Methodology and Assumptions

In this appendix, ICF presents details on the methodology and assumptions applied for the 2021-2040 heat pump analysis. The analysis consists of the following four components:

- **Estimation of Building Energy Requirements** – To estimate the heating and cooling loads in retail and office buildings in each of the four analysis locations
- **Equipment Performance Specifications** – To characterize the heating and cooling efficiencies of GHPs and EHPs in various operating conditions compared to the incumbent system
- **Year 1 Analysis** – To calculate the annual energy requirements to operate the incumbent system and the heat pump options, and to estimate the year 1 operational economics and emissions of each system
- **2021-2040 Projections** – To calculate the overall emissions and operating economics of the heat pump options compared to the incumbent system over the 20-year analysis period

Estimation of Building Energy Requirements

ICF utilized the Department of Energy's Commercial Reference Building models to generate hourly heating and cooling load shapes for retail stores and medium-sized office buildings in each of the four analysis locations. The building models for each location were parsed with latest available weather data (2004 -2018) and simulated on EnergyPlus to obtain hourly electricity and gas consumption values with end-use breakdowns. Figure 27 below shows a snapshot of the hourly data generated through EnergyPlus modeling of a typical office building in Baltimore.

Date/Time	Electricity:Facility [J](Hourly)	Heating:Electricity [J](Hourly)	Cooling:Electricity [J](Hourly)	NaturalGas:Facility [J](Hourly)	Heating:NaturalGas [J](Hourly)
01/01 01:00:00	311,392,254	149,168,050	14,614,490	18,950,406	18,878,406
01/01 02:00:00	268,235,151	109,782,135	12,589,609	11,121,034	11,049,034
01/01 03:00:00	304,606,118	141,038,295	15,535,218	18,769,996	14,699,701
01/01 04:00:00	265,894,355	107,440,662	12,590,286	10,428,120	10,356,120
01/01 05:00:00	286,220,525	127,078,358	12,485,598	15,954,215	11,883,376
01/01 06:00:00	233,418,998	84,406,692	5,900,970	6,446,733	6,374,733
01/01 07:00:00	256,791,517	104,826,549	7,372,451	10,117,533	6,046,621
01/01 08:00:00	197,525,851	80,562,522	5,908,193	4,294,579	4,222,579
01/01 09:00:00	174,122,735	86,353,532	7,289,085	7,722,873	7,650,873
01/01 10:00:00	132,978,523	47,931,336	6,048,250	7,758,758	3,688,261
01/01 11:00:00	123,855,206	38,924,869	5,935,729	569,174	497,174
01/01 12:00:00	99,007,672	20,651,011	2,328,743	4,071,048	-
01/01 13:00:00	102,317,644	22,157,270	3,394,031	72,000	-
01/01 14:00:00	93,920,538	15,125,695	2,766,926	4,071,734	-
01/01 15:00:00	96,386,008	16,997,278	2,622,386	4,070,816	-
01/01 16:00:00	91,300,228	13,224,526	2,047,784	72,000	-
01/01 17:00:00	141,636,076	30,627,441	9,714,783	72,000	-
01/01 18:00:00	193,060,323	42,424,161	7,524,826	4,217,779	146,858
01/01 19:00:00	228,763,857	76,203,593	7,967,747	3,560,561	3,488,561
01/01 20:00:00	227,007,587	75,209,847	7,998,386	10,691,715	6,621,209
01/01 21:00:00	288,495,484	123,727,558	16,735,321	13,428,336	13,356,336
01/01 22:00:00	267,722,294	108,948,911	12,909,977	17,130,632	13,059,335

Figure 27: Snapshot of EnergyPlus Modeling Results for Office Buildings in Baltimore, MD

The EnergyPlus model yields results for electric and natural gas consumption to meet heating and cooling requirements. ICF identified the standard equipment efficiency assumptions used in DOE's commercial reference models to convert electricity/natural gas requirements to absolute hourly heating and cooling load requirements in retail stores and medium-sized offices in all four analysis locations. Figure 28 below shows a snapshot of the actual heating and cooling loads (in BTUs per hour) in a medium-sized office building in Baltimore.

Date/Time	Heating Load (BTU/hr)	Cooling Load (BTU/hr)
01/01 01:00:00	156,057	34,154
01/01 02:00:00	112,690	29,422
01/01 03:00:00	145,158	36,306
01/01 04:00:00	109,939	29,423
01/01 05:00:00	129,756	29,179
01/01 06:00:00	85,031	13,791
01/01 07:00:00	104,181	17,229
01/01 08:00:00	79,744	13,807
01/01 09:00:00	87,851	17,035
01/01 10:00:00	48,338	14,135
01/01 11:00:00	37,356	13,872
01/01 12:00:00	19,618	5,442
01/01 13:00:00	21,049	7,932
01/01 14:00:00	14,369	6,466
01/01 15:00:00	16,147	6,129
01/01 16:00:00	12,563	4,786

Figure 28: Snapshot of Estimated Absolute Heating and Cooling Loads in an Office Building in Baltimore, MD

Equipment Performance Specifications

In this analysis, ICF compares the operating economics and emissions of absorption gas heat pumps (GHPs), engine-driven GHPs, and EHPs against the incumbent options for heating and cooling in retail buildings and offices. This section details the equipment specifications used by ICF for each technology option along with assumptions made to tailor the standard performance specifications to this analysis.

Incumbent Option

Consistent with the industry standard for the small commercial market, packaged rooftop HVAC units (RTU) are considered to be the incumbent thermal system in this analysis with a gas furnace for heating and an electric chiller for cooling. ICF has assumed that the RTU offers an average heating efficiency of 80 percent. The Coefficient of Performance (COP) of electric chillers were modeled based on the performance specifications of a 15-ton Trane electric chiller unit. Based on the performance specifications, ICF applied a cooling COP of 2.8 was applied for the incumbent system.

Absorption Gas Heat Pump

ICF used the performance specifications of the RTAR360-720 30-ton Robur natural gas absorption heat pump to model absorption GHPs in the analysis. ICF used the standard performance specifications of the Robur unit to prepare a distribution of ambient dry bulb temperature ranges and associated heating and cooling COPs. ICF applied the performance specifications for the Robur unit at the default design heating and cooling water outlet temperatures of 122 F and 45 degrees F, respectively. ICF identified that the modeled hourly COP of the Robur GHP ranges from 0.54 to 0.67 in the cooling mode, and 0.87 to 1.35 in the heating mode depending on the ambient temperature. Table 22 shows the heating and cooling COPs of Robur absorption GHPs for various ambient dry bulb temperature ranges.

Table 22: Range of Ambient Dry Bulb Temperatures and Associated Heating and Cooling COPs – Robur Absorption GHP

Cooling COP of Robur GHPs at outlet chilled water temperature of 45 degrees F			
ODB Temperature Range (degree F)		Reported ODB (degree F)	COP
35	60	59	0.67
60	70	68	0.66
70	80	77	0.65
80	90	86	0.64
90	100	95	0.60
100	110	104	0.54
>110		-	0.54
Heating COP of Robur GHPs at outlet hot water temperature of 122 degrees F			
ODB Temperature Range (degree F)		Reported ODB (degree F)	COP
-25	-15	-20	0.87
-15	-10	-13	0.88
-10	0	-4	0.89
0	10	5	0.92
10	15	14	0.96
15	20	19	1.01
20	40	36	1.15
40	50	45	1.26
50	55	50	1.30
55	60	59	1.34
60	70	68	1.35

Engine-driven Gas Heat Pump

ICF used the performance specifications of Aisin 15-ton E Model GHPs to model engine driven GHPs in this analysis. The performance specifications provided by Blue Mountain Energy corresponded to a stackable 15-ton GHP and provides estimates of heating and cooling mode efficiencies at various ambient temperature conditions. ICF used the performance specifications of the Aisin engine at a design indoor wet-bulb temperature of 67 degrees F in the cooling mode, and an indoor dry-bulb temperature of 70 degrees F in the heating mode. ICF further assessed that applying the performance specifications of the system at the rated capacity (100 percent capacity noted in the Aisin engine specifications) throughout the year would yield representative estimates for annual average heating and cooling COPs. Based on the above assumptions, ICF estimated that the modeled hourly COP of engine-driven GHPs ranges from 0.51 to 1.26 in the cooling mode, and 0.89 to 1.46 in the heating mode depending on the ambient temperature.

The performance specifications for the Aisin GHP provides heating and cooling COPs at discrete ambient temperatures. ICF applied temperature ranges around the discrete ambient temperature for each COP value. For instance, the cooling COP at an ambient temperature of 75 degrees F was assumed to represent a range of temperatures from 70 F to 80 F. Establishing these temperature ranges allowed ICF to apply appropriate heating and cooling COPs for each of the 8760 hours in each analysis year depending on the ambient temperature values. Table 23 below shows the heating and cooling COP of Aisin engine driven GHPs with ambient temperatures represented in ranges.

Table 23: Range of Ambient Dry Bulb Temperatures and Associated Cooling COPs - Aisin GHP

Cooling COP at design IWB of 67 degrees F and 100 percent capacity		
ODB Temperature Range (degree F)		COP
50	70	1.26
70	80	1.26
80	90	1.11
90	100	0.97
100	110	0.94
110	120	1.04
120	130	0.51
Heating COP at design IDB of 70 degrees F and 100 percent capacity		
OWB Temperature Range (degree F)		COP
-15	5	0.89
5	15	0.92
15	25	0.94
25	35	0.97
35	41.5	1.09
41.5	46.5	1.15
46.5	55	1.29
55	100	1.46
100	120	1.46

Electric Heat Pump

ICF used the performance specifications of the 15-ton Trane TWA180B electric heat pump unit to model typical EHPs for small commercial applications in the analysis. The chosen EHP unit is rated for heating function up to an ambient temperature of -10 degrees F and would be suitable for application in all four analysis locations. ICF utilized the performance specifications of the unit at a design indoor wet-bulb temperature of 67 degrees F in the cooling mode, and an indoor dry-bulb temperature of 70 degrees F to model the COPs of the EHP. ICF estimated that the COP of the EHP ranges from 3.08 to 3.41 in the cooling mode, and 1.4 to 4.62 in the heating mode.

Similar to the two GHP systems, ICF used the standard performance specifications of the Trane EHP unit to prepare a range of ambient dry bulb temperature and associated heating and cooling COPs to apply to each of the 8760 analysis hours. Table 24 shows the heating and cooling COPs of Trane EHPs for various ambient temperature ranges that ICF applied in this analysis.

Table 24: Range of Ambient Dry Bulb Temperatures and Associated Heating and Cooling COPs – Trane EHP

Cooling COP at design IWB of 67 degrees at 6000 CFM			
ODB Temperature Range (degree F)		Reported ODB (degree F)	COP
60	90	85	3.41
90	100	95	3.40
100	110	105	3.24
110	120	115	3.08
120	130	-	3.08
>130		-	3.08
Heating COP at Return Air DB temperature of 70 degrees F at 6000 CFM			
ODB Temperature Range (degree F)		Reported ODB (degree F)	COP
-10	-6	-8	1.40
-6	0	-3	1.53
0	4	2	1.68
4	10	7	1.74
10	14	12	1.77
14	20	17	2.02
20	25	22	2.18
25	30	27	2.32
30	35	32	2.46
35	40	37	2.60
40	45	42	3.16
45	50	57	3.75
50	55	52	3.91
55	60	57	4.11
60	65	62	4.29
65	70	67	4.47
70	75	72	4.62

Year 1 Analysis

This section describes the calculations carried out by ICF to estimate the Year 1 operating expenses and emissions of each of the heat pump and incumbent options.

Annual Energy Consumption Estimation

ICF prepared estimates for hourly heating and cooling load requirements for offices and retail stores in each analysis location (see Figure 2 for reference).

To estimate the annual electricity and natural gas consumption of the incumbent thermal system, ICF applied an incumbent heating efficiency of 80 percent and a cooling COP of 2.8 for retail stores and 2.9 for offices. These efficiency estimates were applied against the heating and cooling load estimates for each analysis case to estimate the hourly and total annual natural gas and electricity requirements for heating and cooling, respectively in year 1.

ICF modeled the hourly ambient dry bulb and wet bulb temperatures in each analysis location using EnergyPlus weather data. The hourly locational temperature data for each analysis case was correlated with the performance specifications of the Robur GHP, Aisin GHP, and the Trane EHP using the temperature ranges described in Tables 10, 11 and 12, respectively. The estimated hourly cooling and heating efficiencies were used in conjunction with the load profiles of each analysis case to obtain 8760 hourly natural gas consumption (in BTUs) of both GHP options and electricity consumption (in kWh) of the EHP in year 1. These hourly calculations were further translated to total year 1 electricity and/or natural gas consumption for each technology option.

Figure 29 below shows a snapshot of the hourly heating and cooling efficiency and energy consumption estimates prepared by ICF for a retail store in Houston. The figure also displays the estimated hourly gas consumption of the engine-driven Aisin GHP based on the hourly heating and cooling efficiency estimates.

					Aisin Engine GHP			
Date/Time	Outdoor Dry-bulb Temperature (degree F)	Outdoor Wet-bulb Temperature (degree F)	Heating Load (BTU/hr)	Cooling Load (BTU/hr)	GHP Heating COP	GHP Cooling COP	Aisin GHP Gas Consumption - Heating (BTU)	Aisin GHP Gas Consumption - Cooling (BTU)
01/01 01:00:00	42.08	38.98	156,057	34,154	1.09	1.26	142,966	27,024
01/01 02:00:00	42.08	38.98	112,690	29,422	1.09	1.26	103,237	23,280
01/01 03:00:00	42.08	39.45	145,158	36,306	1.09	1.26	132,981	28,727
01/01 04:00:00	42.98	40.49	109,939	29,423	1.09	1.26	100,717	23,281
01/01 05:00:00	44.06	40.89	129,756	29,179	1.09	1.26	118,871	23,088
01/01 06:00:00	46.04	40.53	85,031	13,791	1.09	1.26	77,898	10,912
01/01 07:00:00	46.04	40.53	104,181	17,229	1.09	1.26	95,441	13,633
01/01 08:00:00	44.96	39.84	79,744	13,807	1.09	1.26	73,054	10,925
01/01 09:00:00	44.06	39.00	87,851	17,035	1.09	1.26	80,481	13,479
01/01 10:00:00	48.02	41.22	48,338	14,135	1.09	1.26	44,283	11,184
01/01 11:00:00	51.98	42.19	37,356	13,872	1.15	1.26	32,566	10,976
01/01 12:00:00	51.98	40.27	19,618	5,442	1.09	1.26	17,973	4,306
01/01 13:00:00	51.98	38.25	21,049	7,932	1.09	1.26	19,284	6,276
01/01 14:00:00	48.02	36.38	14,369	6,466	1.09	1.26	13,164	5,116
01/01 15:00:00	46.94	35.56	16,147	6,129	1.09	1.26	14,793	4,849

Figure 29: Estimated Hourly Energy Consumption of the Aisin GHP for a Retail Store in Houston

Economic Analysis

ICF used commercial electricity and natural gas prices reported by EIA to estimate the Year 1 operating expense of each heat pump option. While EIA reports retail electricity prices by utility, natural gas prices are only available at the state level. ICF used utility-specific commercial prices for electricity rates and state-average commercial natural gas prices in this analysis. ICF believes this approach to be appropriate considering that electricity prices see higher locational volatility than natural gas. Most commercial applications are likely to be in urban or suburban locations where electricity prices tend to be higher than the state average. This effect is much less pronounced with natural gas. ICF utilized 2019 commercial retail electricity prices by utility and 2020 state average gas prices and applied nominal escalation rates provided by EIA to estimate 2021 (year 1) utility rates.

Table 25 shows the year 1 electricity and natural gas prices used for each analysis location.

Table 25: Year 1 Electricity and Natural Gas Prices used in the Analysis

City	State	2021 Commercial Electricity Rate (c/kWh)	2021 Commercial Gas Price ($/MMBtu)
Baltimore	MD	11.69	10.91
Houston	TX	10.91	6.47
Las Vegas	NV	9.18	7.40
Minneapolis	MN	10.72	6.77

Using the above electricity and natural gas prices, and energy consumption estimates, ICF calculated year 1 operating expenses of each heat pump option and the incumbent thermal system.

Emissions Analysis

ICF drew from the CHP emissions study prepared for ESC in 2020 to identify year 1 electricity emission rates for each analysis location. ICF has assessed that the non-baseload emissions factor for the eGRID region corresponding to each analysis location would best represent the emissions associated with the incumbent chiller and electric heat pump operations. Table 26 shows the year 1 electricity eGRID emissions factors used by ICF for each analysis location.

Table 26: Year 1 eGRID Electricity Emissions Factors by Analysis Location

City	State	2021 eGRID Electricity Emissions Rate (lbs/MWh)
Baltimore	MD	1,234
Houston	TX	1,222
Las Vegas	ND	1,487
Minneapolis	MN	1,700

For all gas-fired systems including both GHP options, ICF applied a standard carbon emissions rate of 116.9 lbs/MMBtu consistent with the assumptions used in the 2020 CHP emissions study. ICF assumes that the percentage of RNG in the US natural gas supply is zero in 2021.

Using the energy consumption estimates and the electricity and natural gas emission rates, ICF estimated total year 1 operational emissions of each heat pump option and the incumbent system.

2021-2040 Projections

This section details the 20-year operating expense and emissions projections carried out by ICF to evaluate the year-over-year performance of each heat pump option subject to changes in energy prices and electricity emission rates.

Economic Projections

ICF employed EIA's 2021 Annual Energy Outlook (AEO) future energy prices to determine energy price escalation rates leading up to 2040. ICF applied EIA escalation rates to the 2019 or 2020 average electricity and gas prices (depending on data availability) to determine 2021 energy prices. Future-looking forecasts from the EIA Annual Energy Outlook have electricity and gas prices remaining relatively flat over the next twenty years, generally increasing along with inflation. ICF internal forecasts are generally in agreement, and due to the uncertainty in future price impacts of renewable energy mandates, prices are assumed to remain flat in 2021 dollars for the analysis period.

Using the annual energy prices and the energy consumption estimates for each analysis case, ICF estimated the yearly operating expense (in nominal dollars) of each heat pump technology and the incumbent thermal system leading up to 2040 in retail stores and medium-sized offices in all four analysis locations.

Emission Projections

To prepare estimates for the annual operational emissions of each heat pump system, ICF drew from the 2020-2050 CHP emissions study that ICF prepared for Energy Solutions Center in 2020. In the CHP emissions analysis, ICF estimated annual non-baseload electricity emission factors for each eGRID region. The projected emissions factors for each eGRID region takes into account legally binding policy targets for carbon-free and renewable energy. ICF directly drew from the CHP emissions study to characterize the annual non-baseload electricity emission factors leading up to 2040 for each analysis location.

For all gas-fired systems, ICF utilized a standard emission rate of 116.9 lbs/MMBtu. Similar to the electric sector, natural gas is expected to become cleaner owing to the increased production of Renewable Natural Gas (RNG). ICF utilized the findings of a study prepared for the American Gas Foundation (AGF) that provides estimates for economy-wide RNG production up to 2045. RNG production estimates consistent with the 'high production scenario' outlined in the AGF study are used in this analysis. ICF compared the RNG production values with the economy-wide natural gas consumption estimates provided by EIA to estimate annual percentages of RNG in the natural gas supply for each year leading up to 2040. ICF estimates that in the high RNG production scenario, RNG will make up approximately 13 percent of economy-wide natural gas consumption in 2040. The proportion of gas consumption equivalent to RNG production in each year is assumed to carry zero emissions.

ICF applied the annual emission factors for 2021-2040 to estimate the annual operating emissions of each heat pump option and the incumbent system in retail stores and offices in each analysis location. ICF also estimated the cumulative 20-year emissions of each heat pump option for each analysis case.