A STUDY OF INDIRECT GHG EMISSIONS FOR NORTH AMERICAN RESIDENTIAL HEATING AND COOLING EQUIPMENT

Robert B. "Dutch" Uselton, Senior Principal Engineer, Lennox Industries Inc., Carrollton, TX, USA

Abstract: R&D that improves the energy efficiency of residential heating and cooling equipment will reduce site energy consumption, reduce the primary energy necessary to supply the site energy and also reduce the greenhouse gas (GHG) emissions attributable to heating and cooling of homes. This paper benchmarks the performance of common heating and cooling equipment sold in North America with respect to the equivalent CO2 emissions (CO2e) from their use. Operation in several North American cities is examined to see both the effects of local climate and the regional variation in the full-fuel cycle (FFC) power plant efficiency. It turns out that both are important to the understanding the likely GHG impact of heating and cooling equipment selection.

Key Words: efficiency, CO2, GHG, heat pump, furnace

1 INTRODUCTION

Heat pumps have the promise of reducing source energy requirements and CO2e emissions resulting from space conditioning of buildings. This study examines the net source energy, including so-called "precombustion" energy, for two typical residential class space conditioning systems:

- A natural gas furnace with an electric vapor compression air conditioner, and
- A vapor compression heat pump.

The direct and indirect CO2e emissions from annual operation of the equipment are also estimated. The climactic data for six U. S. cities are used and the regional variations in power system characteristics have been taken into account.

Two topics in particular are of current interest to the heat pump design community:

- How significant is the GWP of the refrigerant when estimating life-cycle CO2e emissions, and
- What might be a good target efficiency for a cold-climate heat pump for the northern US and Canada?

Information on these two questions is provided.

2 METHODOLOGY

Heating and cooling systems that combust fossil fuels have direct greenhouse gas emissions; CO2 is a natural byproduct of combustion. They have indirect emissions from the fossil fuel energy consumed in the extraction, processing and transport of the fuel. Moreover, virtually all residential heating and cooling systems consume electricity. There can be substantial indirect greenhouse gas emissions because of the fossil fuel energy used throughout the steps from fuel extraction, fuel transport and electrical generation at the power plant. The extraction process releases other gases, methane in particular, with non-zero global warming potential, GWP. The accounting of all these *equivalent CO2* emissions,

CO_2e, has become a manageable task as data has become available for the various processes that generate them. It is possible to work backward from the electrical and fossil fuel energy consumed on-site to make reasonable estimates of the CO_2e emissions related to that energy use.

2.1 Heating Equipment

In North America, there are a variety of residential space heating systems. Most common is the natural gas-fired warm air furnace. The next most popular system is the electric heat pump. Boiler systems are relatively uncommon except in the northeastern US. In the United States, the Department of Energy's Appliances and Commercial Equipment Standards Program develops test procedures and minimum efficiency standards for residential appliances.

2.1.1 Gas Furnaces

Residential warm air natural gas-fired furnaces are covered by the US Department of Energy's Uniform Test Method for Measuring the Energy Consumption of Furnaces and Boilers (US DOE, Furnaces 1997). The annual fuel utilization efficiency (AFUE) of these products is required to meet a minimum standard of 78%. This metric estimates the seasonal efficiency of natural gas utilization and is based upon the higher heating value of the fuel. It does not consider the electrical energy consumption of the furnace. It is expected that, in the near future, portions of the country with a large number of heating load hours (HLH) will have the minimum AFUE raised to 90%. Canada has a parallel test standard and also uses AFUE for furnace ratings.
The direct CO_2 emissions from warm air furnaces can be calculated just knowing the heating energy supplied to the home over the season, the efficiency (AFUE) of the furnace, and the rate of CO_2 production characteristic for burning natural gas in this type of system. There are also indirect emissions from the furnace's electrical consumption, and from the various emissions that occurred in delivering the natural gas and electricity to the home.

2.1.2 Heat Pumps

In the United States, residential heat pumps are covered by the US Department of Energy Test Procedure for Residential Central Air Conditioners and Heat Pumps (US DOE, Heat Pump 2005). The seasonal heating efficiency of a heat pump is described by the heating seasonal performance factor (HSPF). It is a descriptor with mixed units but, if divided by the number 3.412, gives the dimensionless heating coefficient of performance (HCOP). The HSPF is computed differently for different regions of the United States. The most commonly quoted HSPF is for Region IV, which corresponds to the middle latitudes of the country. The same set of test data is used to calculate the HSPF for the six different regions, the difference comes from how the weightings are changed between the low temperature and higher temperature tests. Note that the HSPF calculation has, built-in, an assumption that auxiliary resistance heat is used when the heat pump does not have sufficient heating capacity. What this means is that the same piece of equipment will have a lower HSPF rating in the colder regions and a higher HSPF in milder regions of the country. Sales of heat pumps in Canada rely on HSPF ratings. The most appropriate "region" designation for most of populous Canada is the US Region V.
Heat pumps can have direct greenhouse gas emissions only if the refrigerant used has a non-zero global warming potential (GWP) and some of the refrigerant leaks from the system. (In the United States, the Environmental Protection Agency requires that R-22 and R410A, the two most common refrigerants, be recovered during servicing and at the end-of-life of the equipment.) Indirect greenhouse gas emissions arise from the use of electricity and from many of the processes related to getting the electricity to the home.

2.2 Cooling Equipment

In the United States, residential air conditioners, including heat pumps operating in cooling mode, are tested and rated according to the same heat pump standard mentioned above. The efficiency descriptor for cooling is called the seasonal energy efficiency ratio (SEER). It is a mixed unit descriptor but, when divided by 3.412, is the dimensionless cooling coefficient of performance (CCOP). The US national minimum SEER is 13 however, for new cooling equipment installations in warm regions of the country it may be raised to 14.
As with heat pumps, direct greenhouse gas emissions can only come from inadvertent leaks of refrigerant. Indirect greenhouse gas emissions can be estimated by working backward from the site electrical energy used to meet the seasonal cooling load, taking into account all of the emissions factors related to getting that electrical energy to the site.

2.3 Climatological Data

Table 1 lists six US cities spanning a range of North American climates. The cities are arranged by US Department of Energy Heat Pump Region number. Heating and cooling design temperatures are listed to indicate the range of winter and summer conditions. The design temperatures are the 99% heating and 2% cooling design temperatures from the 2009 edition of the ASHRAE Handbook of Fundamentals. The assumed summer heat gain rate for the house is 0.607 kW/°C. The cooling design load is calculated by multiplying this heat gain rate times the difference between the design temperature and an 18.3°C (65°F) balance point temperature. The cooling design loads indicate the minimum-sized cooling system needed for the homes. The heating design loads for this study were calculated by following the method for estimating the design heat requirement (DHR) found in the US DOE Test Procedure for Residential Central Air Conditioners and Heat Pumps (US DOE, Heat Pump 2005). Two assumptions were made:

- The 8.3°C heat pump heating capacity is equal to the 35°C cooling capacity (As it turns out, this is frequently true, within +/- 5%.)
- The home's design heat requirement is midway between the Procedures' minimum and maximum DHR values (the calculation method generates a minimum and a maximum)

When these heating design loads are used to generate seasonal heating energy requirements, they give values that are reasonably consistent with home heating energy needs determined from analysis of actual home energy consumption. As might be expected, the variation in heating and cooling loads from home to home, within a region, can vary considerably. Fortunately, the conclusions drawn from this study are not significantly affected by this.

Table 1: Seven Cities Considered in the Analysis

City	State	DOE Region	Cooling Design Temp. (°C)	Heating Design Temp. (°C)	Cooling Design Load (kW)	Heating Design Load (kW)
Orlando	Florida	I	32.8	2.8	8.8	6.2
Ft. Worth	Texas	II	36.0	-2.8	10.7	10.0
Nashville	Tennessee	III	32.2	-8.3	8.4	10.6
Indianapolis	Indiana	IV	30.2	-15.0	7.2	13.2
Minneapolis	Minnesota	V	29.4	-23.3	6.7	16.9
Portland	Oregon	VI	28.6	-1.1	6.2	6.2

2.4 Heating and Cooling Load Estimation

The annual cooling and heating loads are determined using the US Department of Energy Test Procedure for Residential Central Air Conditioners and Heat Pumps (US DOE, Heat

Pump 2005). The procedure provides cooling and heating load hours for each of the defined regions. The annual cooling load is equal to the cooling load hours (CLH) times the cooling design load. The annual heating load, by this procedure, is equal the heating load hours (HLH) times the heating design load times a correction factor of 0.77. In the procedure, the factor is justified as an adjustment that "tends to improve the agreement between calculated and measured building loads."

Table 2:Annual Heating and Cooling Loads for a Typical Home in Seven Cities

City	DOE Region	Annual Cooling Load (kWh)	Annual Heating Load (kWh)
Orlando	I	21100	3600
Ft. Worth	II	19000	9600
Nashville	III	10500	14200
Indianapolis	IV	5600	22900
Minneapolis	V	2800	35700
Portland	VI	1200	13000

2.5 Site Energy Consumption

In developing estimates of annual greenhouse gas emissions for residential cooling and heating systems in North America, it is necessary to work backward from the site energy consumption. In this study, two different classes of equipment are being considered: electric cooling with warm-air natural gas furnace heating <u>and</u> electric heat pumps with auxiliary electrical resistance heat. The efficiency level of the equipment must be specified in order to calculate losses and determine the required input energy. The equipment selections reflect what might be the most likely equipment that would be chosen for installation.

2.5.1 Electric Cooling with Natural Gas Heating

With the SEER level of the air conditioner and the seasonal cooling load both known, it is straightforward to first figure the cooling COP and then the amount of electrical energy consumed to do the work. Table 3 summarizes this information. Note that Indianapolis, Minneapolis and Portland use 13 SEER air-conditioners while the other cities use 14 SEER equipment. The right-most column provides the seasonal cost of operation if the cost of a kWh is equal to the latest official nationally-averaged residential price published by the US Department of Energy (US DOE, Residential Energy Costs).

Table 3: Cooling Season Electrical Energy Use for Electric Air Conditioner

City	DOE Region	Mini-mum SEER	Corres-ponding Seasonal CCOP	Cooling Load (kWh)	Cooling Electrical Energy Use (kWh)	Cooling Season Operating Cost @ $0.115/kWh ($)
Orlando	I	14	4.10	21100	5143	591
Ft. Worth	II	14	4.10	19000	4629	532
Nashville	III	14	4.10	10500	2571	296
Indianapolis	IV	13	3.81	5600	1477	170
Minneapolis	V	13	3.81	2800	738	85
Portland	VI	13	3.81	1200	324	37

The calculations for heating season furnace operation are similar except that there are two energy sources that must be accounted for. Table 4 summarizes heating season results. Note that Indianapolis, Minneapolis and Portland use 90% efficient (90 AFUE) furnaces. The furnaces for homes in Orlando, Ft. Worth and Nashville are 80% efficient (80 AFUE) non-condensing type furnaces. The natural gas cost used is the nationally-averaged residential price published by the US Department of Energy (US DOE, Residential Energy Costs).

Table 4: Heating Season Electrical and Natural Gas Energy for Warm-Air Furnace

City	DOE Region	Min. AFUE	Furnace Electrical Power (kW)	Heating Load (kWh)	Natural Gas HHV Fuel Input (kWh thermal)	Heating Electrical Energy Use (kWh)	Heating Season Op. Cost @ $0.115/kWh & $0.04074/kWh (thermal)
Orlando	I	80	0.5	3600	4400	375	224
Ft. Worth	II	80	0.6	9600	12100	750	578
Nashville	III	80	0.5	14200	17800	875	825
Indianapolis	IV	90	0.4	22900	25400	900	1138
Minneapolis	V	90	0.6	35700	39700	1650	1808
Portland	VI	90	0.4	13000	14500	1100	716

2.5.2 Heat Pump

For the case of heat pumps, the efficiency combination of 14 SEER and 8.5 HSPF will be used for all cities. The corresponding cooling COP for 14 SEER level is 4.103. The cooling COP can be divided into the seasonal cooling load to give the cooling season electrical energy use. In Table 6 an estimate of the cooling season energy usage and operating cost are provided.

Table 5: Cooling Season Electrical Usage for Heat Pump

City	DOE Region	SEER	Cooling COP	Cooling Load (kWh)	Cooling Electrical Energy Use (kWh)	Cooling Season Operating Cost @ $0.115/kWh ($)
Orlando	I	14	4.103	21100	5143	591
Ft. Worth	II	14	4.103	19000	4629	532
Nashville	III	14	4.103	10500	2571	296
Indianapolis	VI	14	4.103	5600	1371	158
Minneapolis	V	14	4.103	2800	686	79
Portland	VI	14	4.103	1200	301	35

Table 6 examines heat pump energy usage. The Region IV 8.5 HSPF designation assumes the minimum design heat requirement in its calculation. For other design heat requirements and for other regions, the HSPF must be recalculated. The design heat requirement is important. It is customary to use a heat pump with oversized cooling capacity in northern climates because of the savings that comes about from higher heating season heat pump output. (This is because less auxiliary resistance heat is needed to meet the load.) Table 6 shows the adjusted HSPF values appropriate for each region, cooling oversize factor and assuming a mid-range design heat requirement. The heating electrical energy use and heating operating cost are also shown.

Table 6: Heating Season Electrical Usage for Heat Pump

City	DOE Region	Region IV (min DHR) HSPF	"Cool-ing Over-size Factor"	HSPF for mid-DHR, Region, Sizing Factor	Heating COP	Heating Load (kWh)	Heating Electrical Energy Use (kWh)	Heating Season Operating Cost @ $0.115/ kWh ($)
Orlando	I	8.5	1	10.59	3.10	3600	1144	130
Ft. Worth	II	8.5	1	9.96	2.92	9600	3300	380
Nashville	III	8.5	1	9.27	2.72	14200	5200	600
Indianapolis	IV	8.5	1.25	8.21	2.41	22900	9500	1100

Minneapolis	V	8.5	1.5	6.73	1.97	35700	18000	2100
Portland	VI	8.5	1.14	10.27	3.01	13000	4300	500

2.6 Energy Extraction, Generation and Distribution Effects

Recently, considerable effort has gone into quantifying the upstream energy consumption and GHG emission effects of the North American energy delivery system. There are national metrics for quantities such as a pre-combustion CO2e factor linked to site-consumed natural gas and regional and national electric power transmission and distribution loss factors. Taking into account these upstream effects has been termed Full Fuel Cycle (FFC) analysis. A report summarizing many of these metrics that may be useful to building engineers is a publicly available publication from NREL (Deru and Torcellini 2007).

2.6.1 Electricity

The electrical distribution system for the continental US is subdivided into three large "interconnections". Alaska and Hawaii have their own systems. Mexico and Canada have separate electrical grids that are not significantly interconnected with the large US system. The "interconnections" are managed by the North American Electrical Reliability Council (NERC). The Western Interconnection encompasses the western US and part of western Canada. The ERCOT Interconnection covers most of Texas. The Eastern Interconnection takes in the remainder of the continental US, west of the Rocky Mountains, and part of Canada. The average electrical transmission loss factor for the aggregate NERC system is 9.9%. ERCOT has a loss factor of 16.1%, the Western, 8.4% and the Eastern, 9.6% (Deru and Torcellini 2007). The fuel/energy sources and types of generating equipment have different proportions in the different interconnects and this is reflected in the regional source energy factors used to estimate the full fuel cycle. The western interconnect uses higher fractions of hydroelectric and natural gas-fired generation and lower fractions of nuclear and coal-fired generation, compared to the other interconnects. Figure 1 shows the full fuel cycle source energy requirements to operate these two different representative cooling/heating systems in the six different cities.

In the process of generating electricity, CO2 is emitted by fossil fuel power plants. There are other greenhouse gas emissions, as well, and it is useful to lump these in with the CO2, on an "equivalent global warming potential" basis, to give an equivalent CO2, or CO2e. This macro-scale assessment looks at all CO2e emissions from the generating stock under consideration, i.e. the electrical energy output from nuclear and hydroelectric power plants is included even though these plants have low or no CO2 emissions. The aggregate NERC system produces 0.620 kg CO2e per kWh of generated electrical output. The corresponding emission factors for the three large interconnects are: ERCOT 0.624, Western 0.486, and Eastern 0.650 (Deru and Torcellini 2007).

There is another part of the electrical power system that has significant CO2e emissions although they are more difficult to aggregate since they come from many smaller sources. These emissions are the result of extracting the power plant fuel from the earth, processing it and then transporting the fuel to the generating facilities. These are termed "precombustion" emission factors. The aggregate NERC system has a precombustion emission factor of 0.0699 CO2e per kWh of generated electricity. That is to say, it is about 1/10 of the generation emission factor. The corresponding precombustion emission factors for the three large interconnects are: ERCOT 0.0947, Western 0.0625 and Eastern 0.0688 (Deru and Torcellini 2007). Finally, to convert emissions related to generation into emissions related to site consumption, the electrical transmission loss factors must be applied.

2.6.2 Natural Gas

Natural gas is composed mainly of methane. It has several other components and the mixture varies over time and geography in North America. In this study, a higher heating value of 37,631 kJ/cubic meter (1010 BTU/cubic foot) will be used. Coincidentally, as with the electrical distribution network, the energy expended to deliver the commodity to the site is around 9%.
CO2e emissions from combustion of natural gas vary according to the combustion system used. In this study, the warm air furnace is the device used for on-site combustion. The on-site combustion CO2e emission factor for a residential furnace burner is 1.93 kg per cubic meter of natural gas. (Less than 1% of this factor comes from non-CO2 emissions.)

All of the non-combustion CO2e emission effects for site-delivered natural gas have been summed and tabulated (Deru and Torcellini 2007) as a "precombustion" emission factor. This factor includes the emissions related to extraction, processing and delivering the fuel. Their estimate is a value of 0.446 kg CO2e per cubic meter of delivered fuel. This is approximately one fourth of the value of the combustion emissions from a warm air furnace.

2.7 Full Fuel Cycle Source Energy

Figure 1, below, shows the full fuel cycle source energy requirements given the previously calculated annual site energy consumption of these systems in the six cities. (The efficiency of delivery of natural gas is assumed to be the same for all cities.) The characteristics of the three NERC interconnects' generation mix and fuel types have been accounted for in the calculation of source energy factors for the electricity used. Energy from renewable energy sources is not considered in the source energy accounting since minimization of non-renewable energy use is the objective for equipment efficiency goals. Note that if national average electrical source energy factors had been used instead, projected source energy requirements, especially for the heat pump, would be overestimated because the Western interconnect has considerable hydroelectric resources.

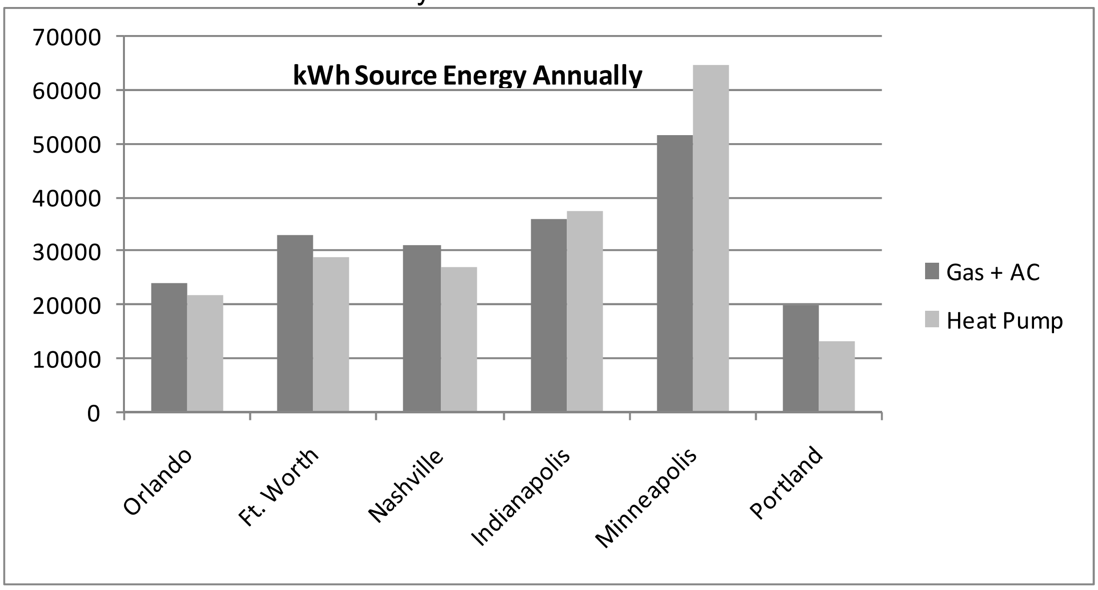

Figure 1: Source Energy Requirements for Two Different Heat/Cooling Systems

2.8 Equivalent CO2 Emissions

Using the identified CO2e emission factors, estimates of direct plus indirect greenhouse gas emissions can be determined for the candidate systems. The emissions include so-called precombustion emissions and account for electrical transmission losses. Table 7 shows the results when national average emission factors are used.

Table 7: Annual kilograms CO2e Emissions Using National Average Emission Factors

City	AC + Furnace Annual CO2e Emissions (kgs)	Heat Pump Annual CO2e Emissions (kgs)
Orlando	5192	4765
Ft. Worth	6817	6012
Nashville	6652	5915
Indianapolis	7575	8238
Minneapolis	10842	14257
Portland	4370	3508

These calculations are repeated in Table 8 but using the NERC interconnect CO2e emissions factors instead of national average emission factors.

Table 8: Annual Kilograms CO2e Emissions Using NERC Interconnect CO2e Emission Factors

City	AC + Furnace Annual CO2e Emissions (kgs)	Heat Pump Annual CO2e Emissions (kgs)
Orlando	5357	4954
Ft. Worth	7226	6615
Nashville	6756	6149
Indianapolis	7646	8564
Minneapolis	10913	14821
Portland	4217	3013

Table 8 CO2e emission estimates best represent reality. As stated in section 2.1.2, CO2e direct emissions from air conditioners and heat pumps only occur if the refrigerant has non-zero GWP and if some refrigerant escapes to the atmosphere. One can overlay the CO2e effects of refrigerant leakage during the life of this class of equipment if a few assumptions are made. For this study, the assumptions about refrigerant leakage have been taken from a 2002 study by Arthur D. Little Inc. (A. D. Little, 2002). They are:

- R410A with 2088 GWP
- 15 year equipment life
- 2% leak rate per year (fleet average)
- 15% loss of refrigerant at end of life (average over all systems).

Additionally, an assumption was made that 0.5 kg refrigerant is required per kW cooling capacity. Figure 2 shows the lifetime CO2e emissions for the systems from Table 8. The dark line at the top of each bar is the CO2e contribution from direct refrigerant emissions, which average 3.9% of total emissions. The conclusion from this is that a system using an alternative refrigerant with zero GWP needs to be at least 96% as efficient in order for there to be net CO2e emission reductions.

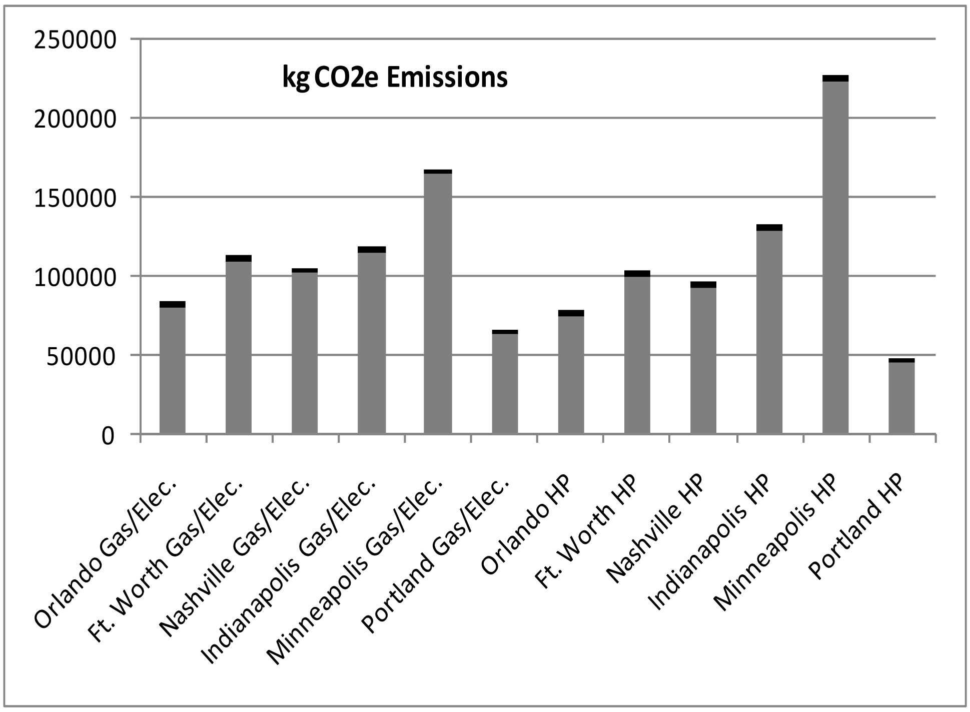

Figure 2: Chart showing 15 year lifecycle kg CO2e Emissions

3 Creating A New Benchmark for Heat Pumps in Cold Climates

Using national average energy costs, the annual operating cost of the heat pumps in this study are lower than the furnaces plus air conditioner operating costs for each city, aside from Minneapolis. (For some cities the operating costs are close to the same.) The CO2e emissions are lower for heat pumps in all cities except Indianapolis (it is close) and Minneapolis. These results suggest a higher efficiency heat pump is needed for cold climates.

A separate study was done looking at only Minneapolis, representative of the northern tier of the US and significant portions of Canada. In this study, the furnace used was a 98% efficient (98 AFUE) model and the cooling unit was kept at 3.81 COP (13 SEER). (While a higher efficiency model of air conditioner could have been used, the number of cooling hours is so low that it would not be a compelling choice.) The heat pump selected was a premium five ton two-stage model with nominal (Region IV) heating COP of 2.68 (HSPF 9+). This heat pump would be configured to use only the first cooling stage to handle the summer cooling load; the high cooling stage would be locked-out. By increasing the ultimate heat pump heating capacity, a considerable energy savings is achieved by displacing electrical resistance auxiliary heating. The results of this analysis are given in Table 9.

Table 9: Minneapolis Results for Best Available Gas/Electric AC and Heat Pump Equip.

Metric	**Units**	**Gas Furnace + Elec. AC**	**Upsized 2-Stage Heat Pump**
Cooling Efficiency	COP	3.81	5.10
Cooling Elec. Energy Used	kWh	706	528
Heating Efficiency	% Effic. / HCOP	98	2.47
Heating Gas Fuel Energy	kWh	35621	---
Heating Elec. Energy Used	kWh	1650	14146
Annual Operating Cost	$	1722	1687
Annual Source Energy	kWh	47012	50522
Annual CO2e Emissions	Kg CO2 equiv.	9956	11563

The best widely available heat pump technology still requires more source energy in cold climates. Annual operating costs are comparable. A heat pump with 10% higher efficiency would use less source energy than the premium furnace plus air conditioner system. A 16% heat pump performance improvement would yield CO2e emissions comparable to the premium furnace plus air conditioner. This suggests that a 20% heat pump heating performance improvement might be a good target for a cold climate heat pump R&D program.

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