Potential Emissions Savings from Refrigeration and Air Conditioning Systems by Using Low GWP Refrigerants

M. BESHR[(1)], V. AUTE[(1)], O. ABDELAZIZ[(2)],
B. FRICKE[(2)], R. RADERMACHER[(1)]
[(1)]3155 Martin Hall, Department of Mechanical Engineering,
University of Maryland College Park, MD, USA 20742, Tel. +1 301 405 8726,
Fax +1 301 405 2025, e-mail: vikrant@umd.edu
[(2)] Oak Ridge National Laboratory,
Energy and Transportation Science Division
Oak Ridge, TN 37831, USA
Fax: 865.574.9338, e-mail: abdelazizoa@ornl.gov

Abstract

Purpose Refrigeration and air conditioning systems have high, negative environmental impacts due to refrigerant charge leaks from the system and their corresponding high global warming potential. Thus, many efforts are in progress to obtain suitable low GWP alternative refrigerants, and more environmentally friendly systems for the future. The system's life cycle climate performance (LCCP) is a widespread metric proposed for the evaluation of the system's environmental impact.

Methods In this paper, the potential emissions reductions in the commercial refrigeration and residential air conditioning systems, made possible by shifting towards more environmentally friendly refrigerants in the US, are presented. First, the current LCCP of the most common commercial refrigeration and residential air conditioning systems is calculated. Then, the LCCP of the baseline systems, when using the potential low GWP alternative refrigerants, is presented. This helps to determine the systems which have the highest potential for emissions reductions.

Results By shifting from the baseline refrigerants, R-404A and R-410A, to the suggested low GWP refrigerants, N-40, and L-41a, in the commercial refrigeration and residential HVAC systems, respectively, a combined drop of 30.43% in the total emissions (i.e. total equivalent mass of emissions in $kgCO_{2eq}$) is obtained. This results from a 50.5% and 28.01% drop in total emissions from supermarket refrigeration systems and residential air conditioning, respectively.

Conclusions Shifting to lower GWP refrigerants in the refrigeration and air conditioning systems helps to reduce the total emissions and negative environmental impacts of these systems. Shifting to a secondary circuit commercial refrigeration system using N-40/L-40, and residential air conditioning and heat pump systems using L-41a helps in reducing the total emissions.

Keywords: LCCP, GWP, alternative refrigerant, Supermarket refrigeration, Residential HVAC, Environmental impact, heat pumps

1. Introduction

Refrigeration and air conditioning needs, whether on the commercial or residential scale, are continuously increasing. This causes an increase in the emissions released from these systems, which has a significant, negative environmental impact. In general, different methods for reducing the negative effects of refrigeration and air conditioning systems on the environment include using low or zero GWP refrigerants, improving systems' efficiency, and designing the system (components sizing, refrigerant used, etc.) while accounting for its environmental impact.

Previously, ozone depleting substances (chlorofluorocarbons (CFCs), and hydrochlorofluoro-carbons (HCFCs)) were commonly used in refrigeration systems. The Montreal protocol (United nations environment programme ozone secretariat 1989) restricted the production and use of such substances which led to a shift towards the use of hydrofluorocarbons (HFCs). The HFCs, however, did not address the global warming potential (GWP) effect. Due to the well-known environmental issues related to global warming, the Kyoto protocol (United Nations 1998) set obligations for the reduction of greenhouse gases (GHG), including the high GWP refrigerants. This led to an increase in the efforts to obtain suitable, low GWP refrigerants that can be used in the future. The studied refrigerants are mostly blends with R-32, R-1234yf, or R-1234ze, in an effort to obtain a balance between low GWP, affordability - if not low cost, safety, and system efficiency. The Air Conditioning, Heating, and Refrigeration Institute (AHRI) launched a global low GWP Alternative Refrigerants Evaluation Program (AREP) to collect industry resources, identify, and evaluate promising alternative refrigerants (AHRI 2011). Among many of the refrigerants tested, R-32, D2Y60 (40% R-32 and 60% R-1234yf), and L-41a (73% R-32, 15% R-1234yf, and 12% R-1234ze) seem to be good candidates to replace R-410A in air source heat pump (ASHP) systems. This is due to their performance, which is comparable with if not better than the R-410A (Alabdulkarem et al. 2013; Burns et al. 2013; Alabdulkarem et al. 2013; Lei et al. 2013; Alabdulkarem et al. 2013). However, a more in depth analysis regarding the performance (especially the annual energy consumption) of the system using these refrigerants, along with the benefits from an environmental perspective, is required. Also, one promising refrigerant for commercial systems is the blend N-40, as it shows comparable performance with significantly lower GWP than R-404A (Motta 2011).

Additionally, designing a system while primarily accounting for its environmental impact requires an evaluation of the system’s overall environmental impact. The widespread metric proposed for this evaluation was presented in the 1999 report of the Montreal Protocol Technology and Economic Assessment Panel (TEAP) (UNEP/TEAP 1999). This metric is the system’s life cycle climate performance (LCCP). The LCCP of the system represents the total carbon dioxide (CO_2) equivalent global warming impact over the total lifetime of the system. The LCCP analysis’s purpose is to evaluate the equivalent mass of carbon dioxide released into the atmosphere due to a system’s performance throughout its lifetime. This includes system construction, operation, and destruction.

The carbon dioxide emissions from a refrigeration system can be divided into two broad categories: direct emissions and indirect emissions. Direct emissions include the environmental impact of the refrigerant, which occurs during system operation, servicing, and at the end of life as well, during the refrigerant production and transportation. Indirect emissions include the environmental impact associated with the production and the distribution of the energy required to operate the refrigeration system, as well the energy associated with production and transportation of the different system components.

Some tools for system evaluation based on LCCP are described in literature. Papasavva et al. (2010) developed a comprehensive life cycle analysis tool of alternative mobile air conditioners (MACs) GREEN-MAC LCCP model and presented the generated sample results. However, this tool is limited to LCCP analysis of MACs. Also, an LCCP evaluation tool for residential heat pumps was developed by Zhang et al. (2011). However, this LCCP evaluation tool does not have LCCP based design capabilities, and had a limited focus which can’t be extended to other types of systems. Furthermore, the calculations in this heat pump tool are done based on temperature bins rather than the more detailed hourly performance data. This heat pump LCCP evaluation tool was used as the core of LCCP evaluation tool transport refrigeration and bus air conditioning systems (Nasuta et al. 2014). An open source modular LCCP evaluation and design based tool for vapor compression systems was developed by the University of Maryland College Park (UMCP) and Oak Ridge National Laboratory (ORNL) (UMCP and ORNL 2013; Beshr et al. 2015). The latter tool, unlike the first two tools, provides design capability of systems based on their LCCP. These tools and other simpler LCCP calculations are used in several studies presented in literature to compare the environmental impact of the different systems or different refrigerants (Arthur D. Little Inc. 2002; Abdelaziz et al. 2012; Beshr et al. 2015; Chen 2007; Hwang et al. 2007; Pham et al. 2012; Spatz et al. 2004; Beshr et al. 2014;

Minor et al. 2010; Kujak et al. 2014). However, these studies do not show the overall impact of shifting towards low GWP refrigerants on the total refrigeration and air conditioning emissions.

In this paper, the LCCP tool (UMCP and ORNL 2013; Beshr et al. 2015) is used to evaluate the total emissions from the most common residential heating, ventilation, and air conditioning (HVAC), and commercial refrigeration systems in the US. The focus on residential HVAC systems is imperative due to their prevalence in the market and high energy consumption. Thus, they have high indirect emissions in addition to largely contributing to the total emissions of all the residential and commercial refrigeration and air conditioning systems. On the other hand, commercial refrigeration systems have a large refrigerant charge and high leakage rates, which leads to high direct emissions. This gives these systems the potential to benefit significantly in the short term by shifting to low GWP refrigerants. This evaluation is performed for the currently used refrigerants by accounting for the differences in the systems' energy consumption in the different climates. Then, the total emissions will be re-evaluated after shifting to low GWP refrigerants (R-32, D2Y60, and L-41a for residential HVAC, and N-40, and L-40 for commercial refrigeration systems).

2. Commercial Refrigeration

There are different types of systems that are used in commercial refrigeration, such as supermarket refrigeration systems, walk-in coolers and freezers, ice machines, and refrigerated vending machines. However, the supermarket refrigeration systems account for the largest portion of the total emissions from the commercial refrigeration systems due to their high charge, annual leak rate, and energy consumption. In this section, the total LCCP from the three main supermarket refrigeration systems used is calculated. These are the centralized direct expansion (DX), distributed, and secondary circuit systems. The number of available supermarket systems as of 2010 is 36149 (Food Marketing Institute 2010), out of which around 70% (25,304), 26% (9,399) and 4% (1,446) are centralized DX, distributed, and secondary circuit, respectively (ICF Consulting 2005). The LCCP calculations are done for six US cities, shown in Table 1, representing different climates.

The hourly emission rate for electricity production is assumed to be equal to the average rate obtained from location-specific standardized reference datasets for emissions (Deru & Torcellini, 2007). This National Renewable Energy Laboratory (NREL) dataset has one average value for each state (obtained based on the different electricity grids covering the state) in the US which is used for each hour in the year. We make this assumption due to lack of available data on hourly emission rate for electricity production. We choose to use this NREL emission database as it uses data from several sources to derive the energy and emission factors for electricity generation. This includes the NREL US Life Cycle Inventory (LCI) Database (NREL, 2005) and the US Environmental Protection Agency (EPA) Emissions & Generation Resource Integrated Database (eGRID) (EPA, 2007). It is worth noting here that although different databases might have different emission factors than those used in this study, the aim of this study is to show the potential savings in total emissions in the US when shifting to more environmentally friendly systems and lower GWP refrigerants. Based on the uncertainty analysis for similar LCCP analysis of supermarket refrigeration systems (Beshr et al., 2015), an uncertainty of 20% in emission factors can causes a difference of up to 20% in the total emissions of the system. However, this results in less than 2% difference between the uncertainties of different systems in the same weather. In other words, while using a different emissions database can make a noticeable difference in the ***absolute*** value of calculated total emissions in one location or over the US, it is unlikely to affect the trends and conclusions shown in the paper (i.e. when comparing the same system in different locations or different systems in the same location).

The aim of this analysis is to include the variation in the weather data and emission rates for each kWh of electricity produced throughout the US in the results. It is assumed that the number of supermarkets in each city as compared to the total number of supermarkets is equal to the fraction of the floor space in the corresponding census region to the total floor space over the US (US Energy Information Administration 2012). However, if more than one city fall within the same census region, the fraction (and hence number of supermarkets) is divided between them according to the population ratio of these cities. The centralized DX system (referred to as S1), distributed system (referred to as S2), and secondary circuit system (referred to as S3) are studied using the baseline refrigerant R-404A, and the low GWP alternative N-40 (N-40/L-40 for S3). The Typical Meteorological Year (TMY) data from the National Solar Radiation Data Base (NREL, 2012) is used as default weather data. These datasets include hourly values for dry-bulb temperature, dew-point temperature, and relative humidity. Also, the default GWP values used in the tool are based on a 100 year time horizon (GWP100) and are obtained from the IPCC Fifth Assessment Report (AR5) (Intergovernmental Panel on Climate Change (IPCC), 2013). The GWP values of other refrigerants which are not listed in AR5 were obtained from AHRI (Amrane 2013) and refrigerant manufacturers (Motta 2011). The GWP and blend composition for the different refrigerants is shown in Table 3.

EnergyPlus (U.S. Department of Energy (DOE)) is used for the hourly energy consumption calculations. The 4181 m^2 single-story supermarket model used in this study is based on the new construction reference supermarket model developed by the U.S. Department of Energy (Deru, et al., 2011). A representative refrigeration load of 308 kW is assumed to be served by each of the three systems with a corresponding charge of 1378 kg, 690 kg, and 669 kg, for S1, S2, and S3, respectively (Beshr et al. 2014). The system lifetime is assumed to be 20 years with service interval of 2 years. Also, the annual leakage rate, refrigerant loss at end-of-life, service leakage rate, and reused refrigerant are 10%, 10%, 5%, and 85%, respectively (Abdelaziz et al. 2012). Note that any other leakage rates used in the LCCP calculations, which do not have a value mentioned in this section, are assumed to be zero.

Figure 1 shows the total emissions for one unit of each of the three systems in each of the climate zones using the baseline refrigerant R-404A and the low GWP blend N-40. Table 2 shows the total emissions ($TonnesCO_{2eq}$) of the supermarket refrigeration systems in four different cases: using R-404A in the current ratio of the system types (S1, S2, and S3), replacing R-404A with N-40 in all the systems, replacing all systems with S2 utilizing N-40, and replacing all systems with S3 utilizing N-40/L-40. Although a system's location does not affect the direct emissions, it affects the indirect emissions. This is due to differences in the weather data (leading to different hourly system electricity consumption) and the hourly emission rate for electricity production between the different cities. It is found that shifting from R-404A to N-40 and using the current system ratio between S1, S2, and S3, causes a drop in the total emissions from 843 Million $TonnesCO_{2eq}$ to 527.7 Million $TonnesCO_{2eq}$ over the lifetime of the system (20 years). This drop in total emissions of 37.4% is a result of 3.92% drop in indirect emissions and 66.76% drop in the direct emissions. The noticeable impact of shifting to low GWP refrigerants in supermarket refrigeration systems on the total emissions is due to their high charge and annual leak rate, especially for the centralized DX system (emissions reduction is 40%, 30%, and 14% for S1, S2, and S3, respectively). Also, shifting towards S3 for all supermarkets results in a further drop in emissions from 527.7 Million $TonnesCO_{2eq}$ to 417.6 Million $TonnesCO_{2eq}$ over the lifetime of the system (13.1% drop in total emissions), which is 50.5% lower than the baseline case.

Figure 2 shows the distribution of total emissions from the supermarket refrigeration systems within the US. It is clear that the south census region (represented by Miami in this study) has the highest emissions. This is due to the relatively high number of supermarket refrigeration units in the south region compared to most of the other regions (e.g. 3.7 times the number of units in the pacific region), and the high total emissions from a single supermarket refrigeration unit in Miami. Although the number of units in the northeast and Midwest regions (represented by Chicago) is even more than the south region, the total emissions in the south region is higher because of the higher total emissions from a single unit in Miami compared to Chicago. However, the pacific region (represented by Los Angeles and Fairbanks in this study) has the lowest emissions. This is due to the low number of supermarket refrigeration units in the pacific region, and the low total emissions from a single supermarket refrigeration unit in some pacific cities such as Los Angeles, as shown in Figure 1. It is worth noting that a similar trend is seen among the different regions for all the cases shown in Table 2.

3. Residential HVAC

There are different types of systems that are used in residential HVAC such as residential unitary air-conditioning (AC) / heat pump (HP) systems, self-contained air conditioning systems, ground source heat pump systems, and dehumidifiers. However, the AC/HP systems account for the largest portion of the total emissions from the residential HVAC systems due to the large portion of installed units, and high annual leak rate. In this section, the total LCCP from an AC/HP system used for cooling and heating is calculated. The number of available AC/HP systems as of 2010 is 70,860,000 out of which 10,320,000 are AC (cooling only) units (U.S. Department of Energy Building Technologies Program 2012). The LCCP calculations were done for the same six US cities, shown in Table 1, representing different climates. The hourly emission rate for electricity production is assumed to be equal to the average rate obtained from location-specific standardized reference datasets for emissions (Deru & Torcellini, 2007). This NREL dataset has one average value for each state (obtained based on the different electricity grids covering the state) in the US which is used for each hour in the year. We make this assumption due to lack of available data on hourly emission rate for electricity production. We choose to use this NREL emission database as it uses data from several sources to derive the energy and emission factors for electricity generation. This includes the NREL LCI Database (NREL, 2005) and the EPA eGRID (EPA, 2007). It is assumed that the number of systems in each city as compared to the total number of systems is equal to the fraction of the homes in the corresponding census region to the total number of homes over the US (US Energy Information Administration 2012). However, if more than one city fall within the same census region, the fraction (and hence number of AC/HP systems) is divided equally among them. The AC/HP system is studied using the baseline refrigerant R-410A, and the low GWP alternatives R-32, D2Y60, and L-41a. The LCCP of the system in the cooling only mode is used to calculate the LCCP of the AC systems while the addition of the cooling and heating modes is used to calculate the emissions of the AC/HP systems. The GWP and blend composition for the different refrigerants is shown in Table 3 where the GWP100 of the refrigerants are obtained from the IPCC AR5 (Intergovernmental Panel on Climate Change (IPCC), 2013), AHRI (Amrane 2013) and refrigerant manufacturers (Motta 2011).

The simulated AC/HP system is similar to the system experimentally tested in the AHRI low GWP AREP report #20 (Alabdulkarem et al. 2013). The system uses R-410A as the baseline refrigerant with a system charge of 4.54 kg. The AHRI standard 210/240 (ANSI/AHRI 2008) is used for hourly load calculations. An in house vapor compression system simulation tool (Winkler et al. 2008) is validated against the experimental data in the report (Alabdulkarem et al. 2014). This simulation tool is used in the LCCP tool for the electricity consumption calculation. As per the AHRI standard 210/240 (ANSI/AHRI 2008), if the ambient temperature is higher than 291.5 K (65°F), the system operates in cooling mode while for lower ambient temperatures, the system operates in the heating mode. The system's lifetime is assumed to be 15 years, with a service interval of 5 years. Also, the annual leakage rate, refrigerant loss at end-of-life, service leakage rate, and reused refrigerant are 12%, 65%, 5%, and 35%, respectively (ICF International 2009). Note that any other leakage rates used in the LCCP calculations, but which do not have a value mentioned in this section, are assumed to be zero.

Figure 3 shows the total emissions for one AC/HP unit of each of the refrigerants in each of the studied climate zones. The indirect emissions in Los Angeles are much lower than the other cities for all the refrigerants, which is mainly due to two factors. First, this city has a mild climate, therefore the heat pump will operate for shorter periods and the system's annual electricity consumption will be lower compared to the other cities. The second reason is that the hourly emission rate for electricity production is low for this city. For example, the emission rate in Phoenix is about 2 times that of Los Angeles. Also, Figure 3 shows that for the AC/HP system, unlike the supermarket refrigeration systems, the direct emissions represent a small fraction of the total emissions of a single unit of the system. Thus, the percentage drop in total emissions from the AC/HP system when using low GWP refrigerants is expected to be lower than the drop from the supermarket refrigeration systems. However, this occurs only if the low GWP refrigerant used in the AC/HP provides the same performance as the high GWP refrigerant. If the low GWP refrigerant provides better performance than the high GWP refrigerant, the total emissions of the system using the low GWP refrigerant would decrease significantly, and vice versa.

For all cities, L-41produces the lowest total emissions. Although L-41a does not have the lowest GWP and direct emissions (D2Y60 has the lowest GWP and direct emissions), it shows comparable system performance, low energy consumption, and indirect emissions. Thus, selecting the more environmentally friendly system's refrigerant depends not only on the refrigerant's GWP, but also its effect on the system's performance (electricity consumption).

Table 4 shows the total emissions (TonnesCO_{2eq}) for the AC/HP system after considering all the units in each city. Shifting from R-410A to L-41a causes a drop in the total emissions from 5.22 Billion TonnesCO_{2eq} to 3.76 Billion TonnesCO_{2eq} over the lifetime of the system (15 years). This drop in total emissions of 28.0% is a result of 3.7% drop in the indirect emissions and 74% drop in the direct emissions. Figure 4 shows the distribution of total emissions from the AC/HP systems within the US. The south region (represented by Miami in this study) has the highest emissions, although Miami does not have the highest total emissions for a single AC/HP unit, as shown in Figure 3. This is mainly because of the high number of AC/HP units in the south region compared to other regions (e.g. 3.4 times the number of units in the pacific region). Although the number of units in the northeast and Midwest regions (represented by Chicago) is more than the south region, the total emissions in the south region is higher due to the higher total emissions from a single unit in Miami compared to Chicago. Additionally, the pacific region (represented by Los Angeles and Fairbanks in this study) has the lowest emissions. This is due to the low number of AC/HP units in the pacific region, and the low total emissions from a single AC/HP unit in some pacific cities such as Los Angeles, as shown in Figure 3. However, both refrigerants (R-410A and L-41a) show a similar trend among different regions.

Although the LCCP of a single supermarket refrigeration unit is much higher than the LCCP of an AC/HP unit, the total emissions from the residential HVAC systems is much higher (8.5 times) than the total emissions from the commercial refrigeration systems. This is due to the large number of units of residential HVAC systems compared to the commercial refrigeration system.

4. Conclusion

In this paper, a universal tool for LCCP evaluation and LCCP based design of vapor compression systems is used to calculate the drop-in total emissions from refrigeration, air conditioning, and heat pumping when shifting to low GWP refrigerants. The study is performed in 6 US cities representing different climates. The LCCP of the centralized DX, distributed, and secondary circuit supermarket refrigeration systems is calculated using the baseline R-404A and the low GWP alternative N-40. The drop in the total emissions from the supermarket systems is 50.5%, almost all of which is due to drop in the direct emissions. Furthermore, a residential AC/HP system is simulated using the baseline R-410A and the low GWP alternatives R-32, D2Y60, and N-40. Among the three latter refrigerants, the N-40 shows a good balance between the competitive system performance (energy consumption), and the low GWP (direct emissions). The drop in the total emissions from the AC/HP is 28.01%. The combined drop in total emissions from all the studied systems is 30.43% when shifting from the baseline to low GWP refrigerants, and towards the more environmentally friendly refrigeration systems. Hence, using S3 supermarket refrigeration systems utilizing N-40 and an AC/HP system utilizing L-41a causes an annual drop in emissions of 118.8 Million TonnesCO_{2eq}.

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Supporting Information Available

This tool is available free of charge via the internet at: http://lccp.umd.edu/ornllccp/

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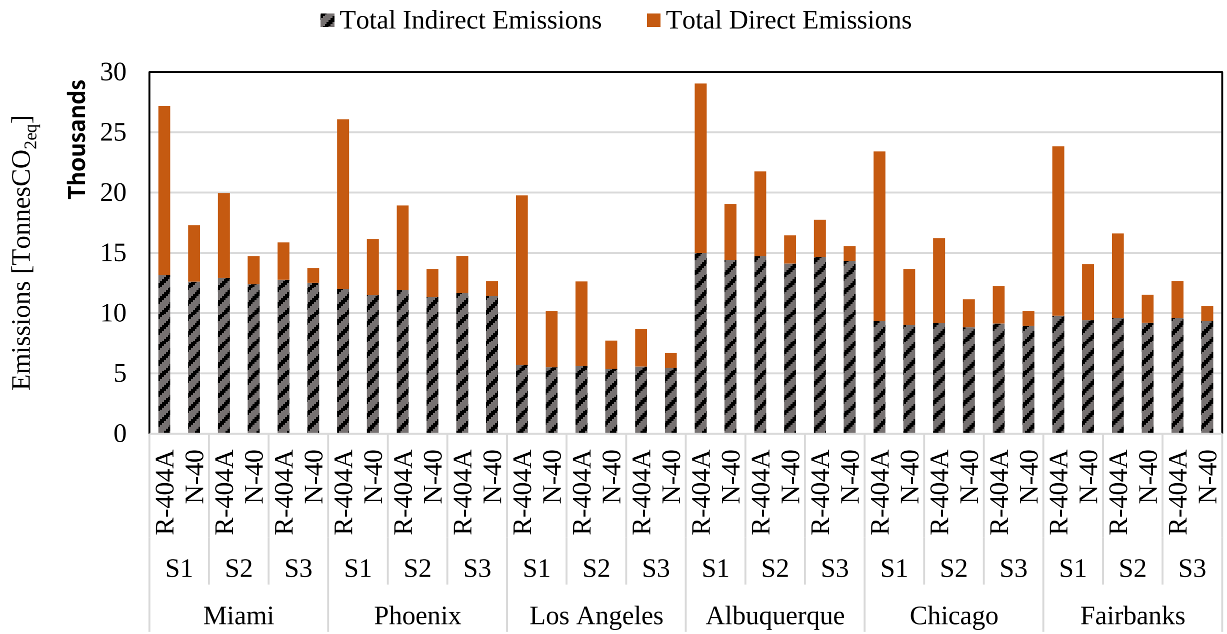

Figure 1: Total emissions of supermarket refrigeration systems (Beshr, et al., 2014).

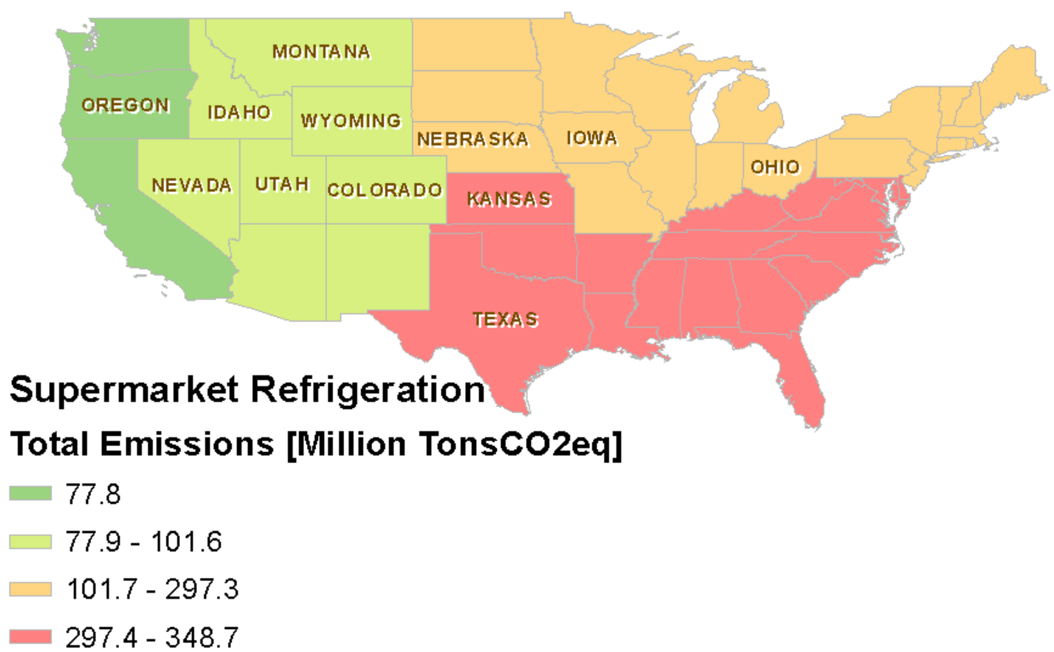

Figure 2: Distribution of total emissions from supermarket refrigeration systems using R-404A over the US regions

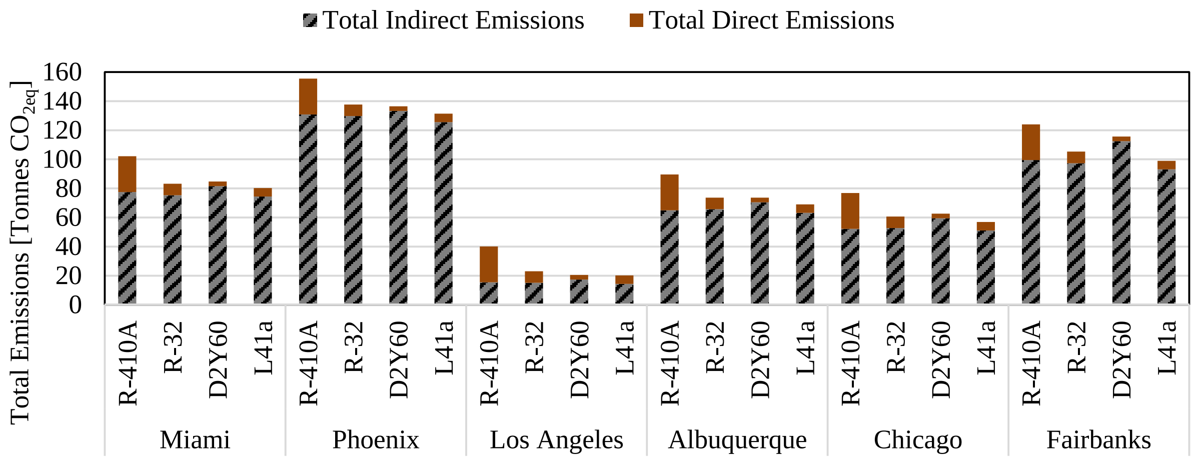

Figure 3: ASHP System's total emissions

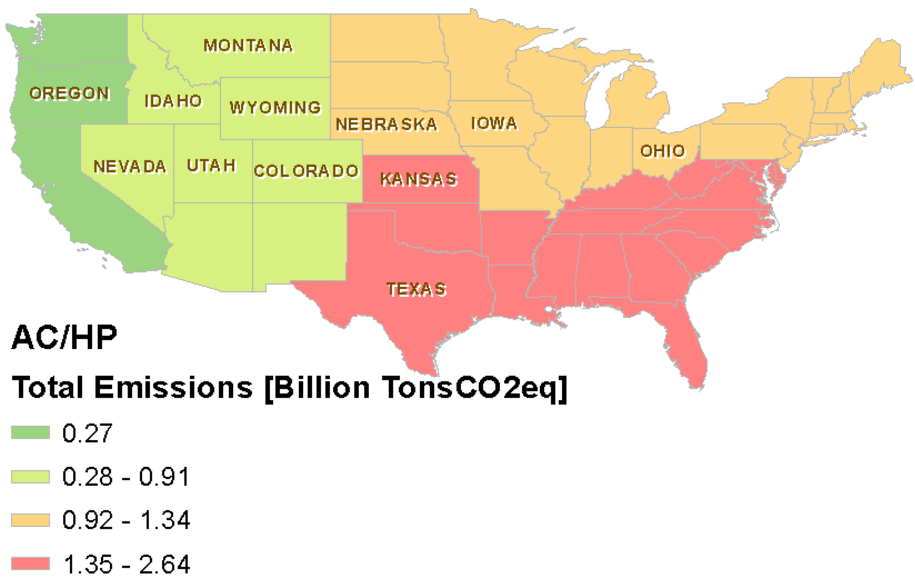

Figure 4: Distribution of total emissions from AC/HP systems using R-410A over the US regions

Table 1: Climate zones and cities used in the LCCP analysis

Climate Zone	City	Annual Average Temperature (°C)
1A	Miami, FL	24.9
2B	Phoenix, AZ	23.8
3B	Los Angeles, CA	17.3
4B	Albuquerque, NM	14.2
5A	Chicago, IL	10.0
8	Fairbanks, AK	-2.1

Table 2: Total emissions (Million TonnesCO_{2eq}) for each supermarket refrigeration system

	Baseline (R-404A)	S1/S2/S3 (N-40)	S2 (N-40)	S3 (N-40)
Miami	348.7	234.4	209.5	195.6
Phoenix	69.8	43.9	39.1	36.1
Los Angeles	112.7	60.6	28.8	25.0
Albuquerque	11.0	4.7	15.7	14.8
Chicago	297.3	183.8	159.2	145.3
Fairbanks	3.5	0.3	0.9	0.8
Total	**843.0**	**527.7**	**453.1**	**417.6**

Table 3: Blend composition and GWP values of the used refrigerants

Refrigerant	Composition (Mass %)	GWP
R-404A	R-125/R-134a/R-143a (44/4/52)	3,922
R-407F	R-32/R-125/R-134a (30/30/40)	1,824
L-40	R-32/R-152a/R-1234yf/R-1234ze (40/10/20/30)	285
N-40	R-32/R-125/R-134a/R-1234yf (25/25/20/30)	1,300
R-410A	R-32/R-125 (50/50)	2,088
R-32	R-32 (100)	675
D2Y60	R-32/R-1234yf (40/60)	272
L-41a	R-32/R-1234yf/R-1234ze(E) (73/15/12)	494

Table 4: Total emissions (Billion TonnesCO_{2eq}) for AC/HP system

	R-410A	L-41a
Miami	2.64	2.06
Phoenix	0.85	0.71
Los Angeles	0.22	0.07
Albuquerque	0.17	0.13
Chicago	1.34	0.77
Fairbanks	0.007	0.003
Total	**5.22**	**3.76**