An Evaluation of the Environmental Impact of Different Commercial Supermarket Refrigeration Systems Using Low Global Warming Potential Refrigerants

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ABSTRACT

Commercial refrigeration systems consumed 1.21 Quads of primary energy in 2010 and are known to be a major source for refrigerant charge leakage into the environment. Thus, it is important to study the environmental impact of commercial supermarket refrigeration systems and improve their design to minimize any adverse impacts. The system's Life Cycle Climate Performance (LCCP) was presented as a comprehensive metric with the aim of calculating the equivalent mass of carbon dioxide released into the atmosphere throughout its lifetime, from construction to operation and destruction. In this paper, an open source tool for the evaluation of the LCCP of different air-conditioning and refrigeration systems is presented and used to compare the environmental impact of a typical multiplex direct expansion (DX) supermarket refrigeration systems based on three different refrigerants as follows: two hydrofluorocarbon (HFC) refrigerants (R-404A, and R-407F), and a low global warming potential (GWP) refrigerant (N-40). The comparison is performed in 8 US cities representing different climates. The hourly energy consumption of the refrigeration system, required for the calculation of the indirect emissions, is calculated using a widely used building energy modeling tool (EnergyPlus). A sensitivity analysis is performed to determine the impact of system charge and power plant emission factor on the LCCP results. Finally, we performed an uncertainty analysis to determine the uncertainty in total emissions for both R-404A and N-40 operated systems. We found that using low GWP refrigerants causes a considerable drop in the impact of uncertainty in the inputs related to direct emissions on the uncertainty of the total emissions of the system.

1. INTRODUCTION

A typical supermarket with a traditional multiplex direct expansion (DX) refrigeration system requires 1400-2300 kg of refrigerant, and has an average annual charge loss of 30% (Southern California Edison, 2004). High or moderate global warming potential (GWP) refrigerants in conjunction with these high refrigerant leak rates contributes to significant direct CO_{2eq} emissions. Also, a typical 3300 m^2 supermarket consumes 2-3 GWh of energy annually which results in substantial indirect CO_{2eq} emissions. These high direct and indirect CO_{2eq} emissions contribute to the significant negative environmental impact of commercial refrigeration systems. Methods for reducing the negative environmental impact of commercial refrigeration systems include improving the efficiency of the refrigeration systems, using low or zero GWP refrigerants, reducing refrigerant leaks, and designing systems (component sizing, refrigerant selection, etc.) with environmental impact as one of the main performance criterion.

There are several ongoing efforts to develop suitable low GWP alternative refrigerants for use in commercial refrigeration. The refrigerants proposed so far are mostly blends comprised of R-32, R-1234yf or R-1234ze, with an effort to obtain balance between low GWP, affordability, safety, and system efficiency. The Air Conditioning, Heating and Refrigeration Institute (AHRI) launched a global low GWP Alternative Refrigerants Evaluation Program (AREP) to gather industry resources to identify and assess promising alternative refrigerants (Wang, et al., 2012). One of the promising refrigerants for commercial systems is the blend N-40, which shows competitive performance and much lower GWP than R-404A (Motta, 2011).

Moreover, designing a system while primarily accounting for its environmental impact requires an evaluation of the system's overall environmental impact as a function of its design parameters. The system's Life Cycle Climate Performance (LCCP) was presented in the report of the Montreal Protocol Technology and Economic Assessment Panel (TEAP) (UNEP/TEAP, 1999) as the most comprehensive metric proposed for this evaluation. The LCCP of a system represents the total CO_{2eq} global warming impact over the lifetime of the system. It represents the equivalent mass of CO_2 released into the atmosphere due to the system's performance, throughout its lifetime, from system construction through system operation and system destruction. The CO_{2eq} emissions from a refrigeration system can be divided into two broad categories: direct emissions and indirect emissions. Direct emissions include the environmental impact of leakage of refrigerant which occurs during system operation, servicing, and at the end of life as well as during the refrigerant production and transportation. Indirect emissions include the environmental impact associated with the production and distribution of the energy required to operate the refrigeration system as well energy associated with production and transportation of the different system components.

The LCCP concept has been used to compare the overall environmental impact of selected HFCs to other fluids and technologies in applications such as automobile air conditioning, residential and commercial refrigeration, unitary air conditioning, and HVAC chillers (ADL, 2002). In addition, some tools for system evaluation based on LCCP have been presented in the literature. One of these tools is the comprehensive life cycle analysis tool of alternative mobile air conditioners (MACs), GREEN-MAC LCCP, which was developed by Papasavva et al. (2010). However, this tool is limited to LCCP analysis of MACs. Also, an LCCP analysis tool specifically developed for residential heat pumps was presented by Zhang et al. (2011).

This paper introduces a modular open-source framework for LCCP-based design of vapor compression systems. A tool (computer program) based on this framework is used to compare the LCCP of a multiplex direct expansion commercial refrigeration system, using three refrigerants (R-404A, R-407F, N-40), in eight US cities representing different climate zones. An uncertainty analysis is conducted on the system to determine the effect of the uncertainty of each LCCP tool input on total system emissions. Finally, a sensitivity analysis is performed to identify the relative importance of refrigerant charge and electricity production emissions when using lower GWP refrigerants.

2. LCCP FRAMEWORK

Fig. 1 shows the LCCP framework (ORNL, and UMCP, 2013). The core module in this framework is the open-source LCCP calculation methodology. This module is connected to three input modules: the system performance model, the load model, and the standardized reference data sets for emissions and weather. These modules interact with each other via standardized communication interfaces that describe the data input-output processes. Due to the modular nature of the framework, any individual module can be replaced with a user-defined module. This makes the framework highly extensible and suitable for analyzing a variety of systems.

The system performance model uses the weather data to calculate the hourly electric energy consumption of the system at full capacity. In turn, the load model provides the hourly load values required for the calculation of the actual hourly electric energy consumption of the system. This modified hourly electric energy consumption is multiplied by the hourly emission rate for electricity production, obtained from the standardized reference datasets for location-specific emissions, to obtain the hourly emission due to energy consumption of system. The technical report by Deru & Torcellini (2007) is the source of the default values for the hourly emission rate for specified locations within the USA used in the tool. Different building energy modeling tools such as EnergyPlus (2012) can be used in the load module to determine the hourly load profile only, or both the hourly load and the system electric energy consumption. In the latter case, a separate system performance model is not required.

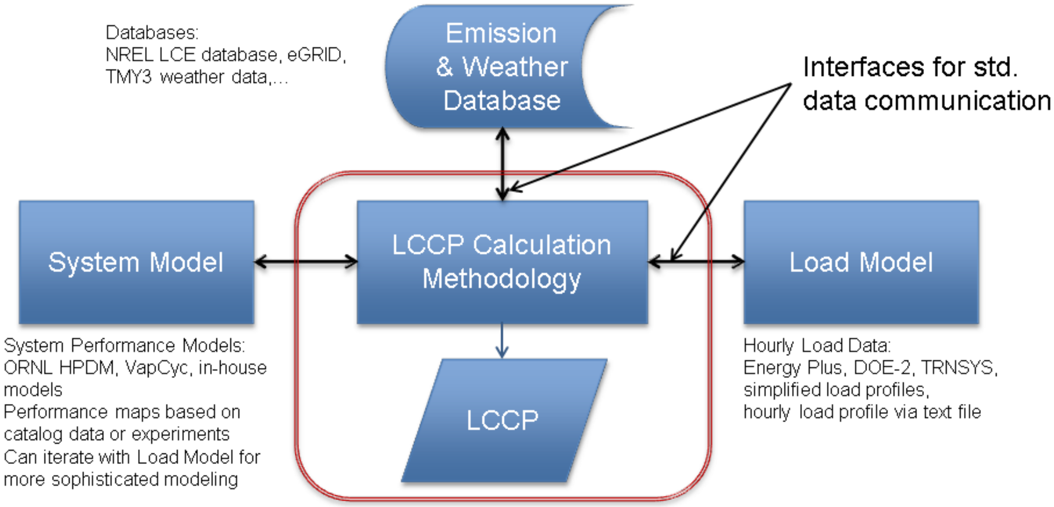

Figure 1: LCCP Framework

The Typical Meteorological Year (TMY) data from the National Solar Radiation Data Base (NREL, 2012) is used as the default weather data. These datasets include hourly values for dry-bulb temperature, dew-point temperature, and relative humidity. The tool has 47 built-in cities with the capability of adding user-defined cities.

The default GWP values used in the tool are based on a 100 year time horizon (GWP_{100}) and are obtained from the IPCC Fifth Assessment Report (AR5) (2013). The GWP values of other refrigerants which are not listed in AR5 were obtained from the AHRTI report by Zhang *et al.* (2011), based on values provided by manufacturers, or compiled from publicly available information.

3. EMISSION CALCULATIONS

3.1. Direct Emissions

The six contributors to the direct emissions may be combined to yield the total direct emissions, Em_{direct}, as shown in Eq. (1-6) where $Em_{ref,leak}$ are due to refrigerant leakage, Em_{acc} are due to accidents, Em_{serv} are due to servicing, $Em_{ref,EOL}$ are due to refrigerant leakage at end-of-life, $Em_{ref,prod}$ are due refrigerant production and transportation, $Em_{reaction}$ is the reaction byproduct of the atmospheric breakdown of the refrigerant emissions. The latter term is a user-input value with the default value being zero.

$$Em_{direct} = Em_{ref,leak} + Em_{acc} + Em_{serv} + Em_{ref,EOL} + Em_{ref,prod} + Em_{reaction} \quad (1)$$

$$Em_{ref,leak} = charge * system\,lifetime * annual\ leak\ rate * GWP \quad (2)$$

$$Em_{acc} = charge * system\,lifetime * annual\,accident\,leak\,rate * GWP \quad (3)$$

$$Em_{serv} = total\,number\,of\ services * charge * servicing\,leak\,rate * GWP \quad (4)$$

$$Em_{ref,EOL} = percent\,of\ refrigerant\,lost\,at\,end\,of\ life * charge * GWP \quad (5)$$

$$Em_{ref,prod} = ref.\,production\ \&transportation\,leak\,rate * charge * GWP \quad (6)$$

3.2. Indirect Emissions

The total indirect emissions, $Em_{indirect}$, can be calculated as shown in Eq. (7-11). There are six contributors to the indirect emissions: emissions due to energy required to manufacture the system, $Em_{sys,man}$, emissions due to energy used to manufacture the refrigerant, $Em_{ref,man}$, emissions due to energy required to recycle the system, $Em_{sys,EOL}$, lifetime emissions due to electric energy consumption, Em_{elec}, emissions due to refrigerant recycling and disposal at end-of-life, $Em_{ref,disp}$, and emissions due to energy used to transport the system, $Em_{sys,trans}$. The latter two terms are user-input values with the default values being zero.

$$Em_{indirect} = Em_{sys,man} + Em_{ref,man} + Em_{sys,EOL} + Em_{elec} + Em_{ref,disp} + Em_{sys,trans} \quad (7)$$

$$Em_{sys,man} = mass\ of\ each\ material * CO_2\ equivalent \quad (8)$$

$$Em_{ref,man} = charge * (1 + system\ lifetime * annual\ leak\ rate - percent\ of\ reused\ refrigerant) * CO_2 equivalent\ emissions\ for\ virgin\ refrigerant \quad (9)$$

$$Em_{sys,EOL} = energy\ of\ recycling\ of\ metals * mass\ of\ metals * CO_2\ equivalent\ of\ metals + energy\ of\ recycling\ of\ plastics * mass\ of\ plastics * CO_2\ equivalent\ of\ plastics \quad (10)$$

$$Em_{sys,elec} = system\ lifetime * \sum_{n=0}^{8760} hourly\ energy\ consumed * emission\ rate\ for\ electricity\ production \quad (11)$$

3.3. Total Emissions

Finally, the total emissions (Em_{total}), representing the LCCP and including the contributions from direct and indirect emissions, is calculated as shown in Eq. (12).

$$Em_{total} = Em_{direct} + Em_{indirect} \quad (12)$$

4. SYSTEM MODEL

The EnergyPlus model used in this study is a 4181 m^2 single-story supermarket and is based on the new construction reference supermarket model developed by the U.S. Department of Energy (Deru, et al., 2011). The analysis is performed for eight US cities representing different climate zones, as shown in Table 1. Moreover, various leakage rates and refrigeration system operating parameters required by the LCCP tool are shown in Table 2 (Abdelaziz, et al., 2012). Note that the remaining leakage rates that appear in Eq. (1-6), but which do not appear in Table 2, are assumed to be zero. The GWP and blend composition for the different refrigerants is shown in Table 3 where the GWP of the refrigerants are obtained from the IPCC Fifth Assessment Report (AR5) (2013), AHRI (Amrane, 2013) and refrigerant manufacturers (Motta, 2011). The total refrigerant charge in each of the systems is based on data provided by PG&E (Pacific Gas and Electric Company, 2011).

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
4C	Seattle, WA	11.4
5A	Chicago, IL	10.0
6B	Helena, MT	7.2
7	Duluth, MN	4.3
8	Fairbanks, AK	-2.1

Table 2: Refrigerant leakage rates and system operating parameters

Annual leakage rate	10	%
Refrigerant loss at end-of-life	10	%
System lifetime	20	years
Service interval	2	years
Service leakage rate	5	%
Reused refrigerant	85	%

Table 3: Refrigerant blend compositions and GWP values

Refrigerant	Composition	GWP
R-404A	R-125/R-134a/R-143a	3943
R-407F	R-125/ R-134a /R-32	1674
N-40	R-125/ R-134a /R-32/R-1234yf/R-1234ze	1273

The multiplex DX refrigeration system consists of two medium temperature (MT) DX racks and two low temperature (LT) DX racks. Rack MT1 and rack LT1 are coupled via a mechanical subcooler and the two racks share one condenser. Similarly, rack MT2 and rack LT2 are coupled via a mechanical subcooler and the two racks share one condenser. The refrigeration load and refrigerant charge for each compressor rack is given in Table 4.

Table 4: Multiplex DX system specifications

Compressor Rack	Refrigeration Load (kW)	Charge (kg)	Source of Mechanical Subcooling
MT1	167.1	748	--
MT2	52.8	236	--
LT1	64.6	290	MT1
LT2	23.4	104	MT2
Total:	**307.9**	**1378**	

5. RESULTS AND DISCUSSION

5.1 LCCP Analysis

Fig. 2 shows the total CO_{2eq} direct emissions of the refrigeration system, using the three refrigerants (R-404A, R-407F, and N-40). The direct emissions are dependent on the system charge and the type of refrigerant. However, note that the direct emissions are not affected by the system location. Hence, systems with N-40 have the lowest direct emissions while systems with R-404A have the highest direct emissions.

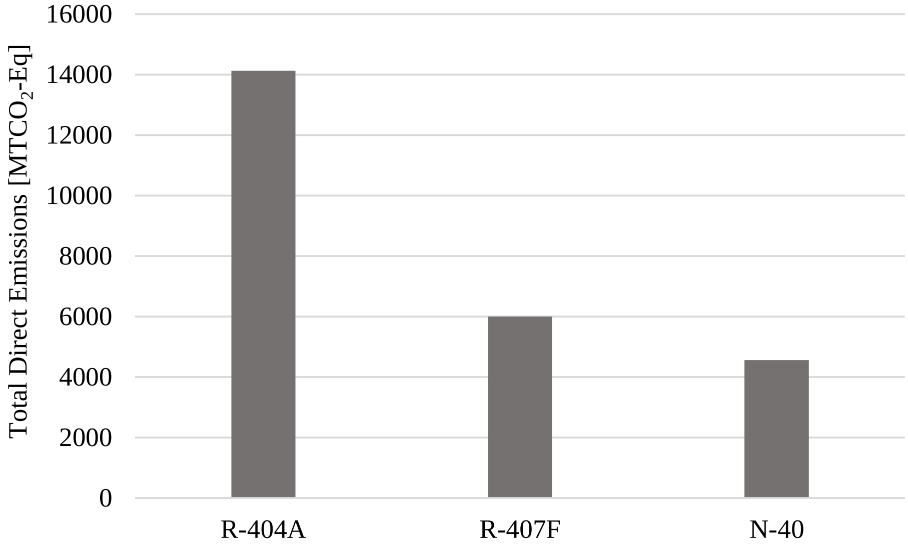

Figure 2: Total CO_{2eq} direct emissions of the refrigeration system for different refrigerants

Fig. 3 shows the total CO_{2eq} indirect emissions in each city for the different refrigerants used. It can be seen that although system location does not affect the direct emissions, it does affect the indirect emissions. This is due to differences in both the weather data (leading to different hourly system electric energy consumption) and the hourly emission rate for electricity production between the cities. Note that the indirect emissions in Seattle and Los Angeles are much lower than the other cities for all the refrigerants although it might have higher annual electric energy consumption. This is mainly due to the fact that the hourly emission rate for electricity production is low for these two cities. For example, the emission rate for electricity production in Phoenix is about two times that in Los Angeles and four times that in Seattle.

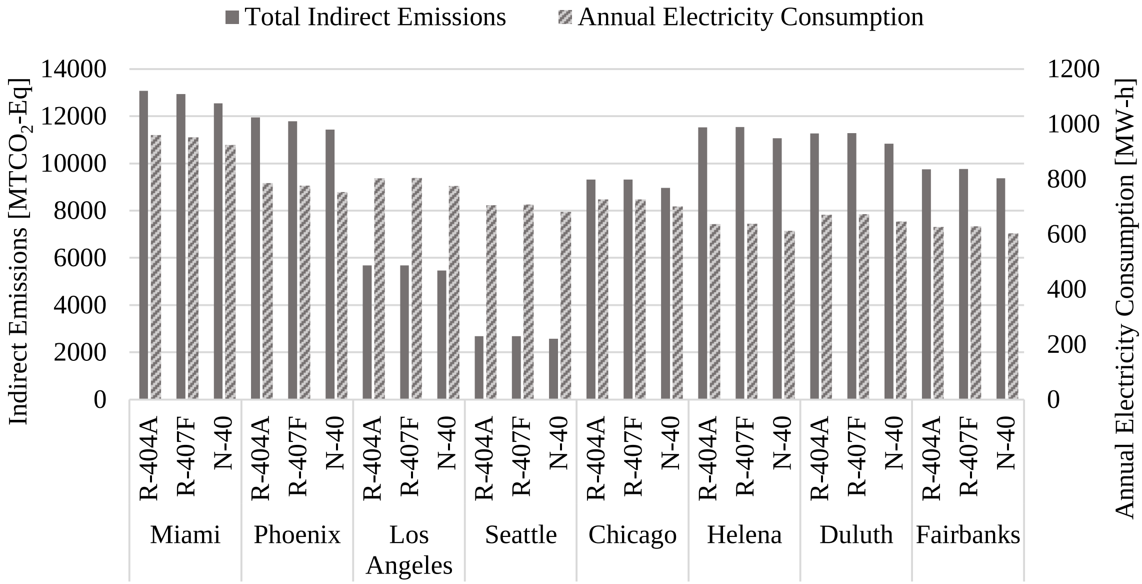

Figure 3: Total indirect CO_{2eq} emissions and annual electricity consumption of the refrigeration system for different refrigerants

For all cities, the indirect emissions of the refrigeration system are generally the lowest when using N-40. Thus, for all locations, N-40 has the lowest total CO_{2eq} emissions as can be seen in Fig.4. It is worth noting that for multiplex DX commercial refrigeration systems in general, the direct emissions are just as significant as or more significant than the indirect emissions with regard to the total emissions. Therefore, using low GWP refrigerants in multiplex DX systems would result in a noticeable drop in the system's total emissions, as shown in Fig. 4. This is in contrast to residential refrigeration and air conditioning systems, where the system's direct emissions are a small fraction of the total emissions; hence refrigerant GWP will be of less significance to the LCCP.

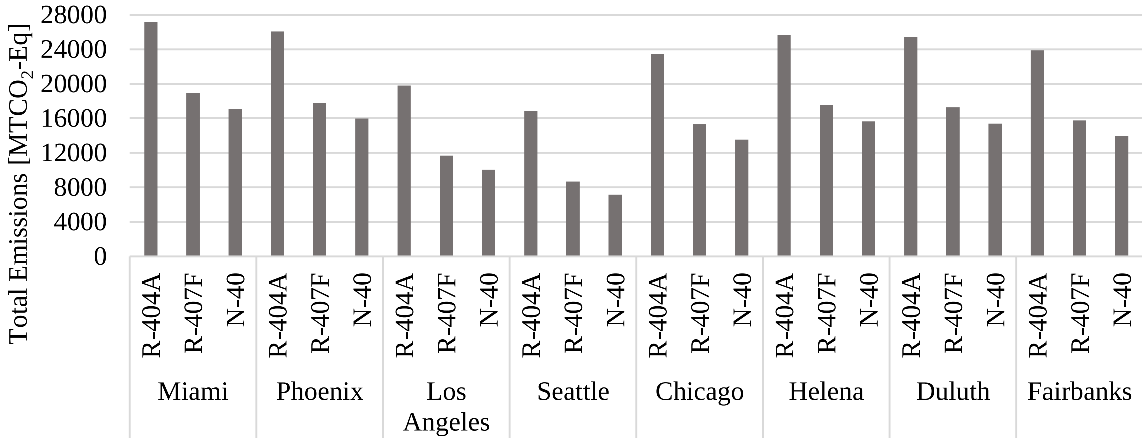

Figure 4: Total CO_{2eq} emissions of the refrigeration system for different refrigerants

5.2 Sensitivity Analysis

A sensitivity analysis of the effect of a 10% change in the refrigerant charge and the hourly emission rate for electricity production on the total CO_{2eq} emissions of the system in Chicago, Seattle, and Miami was performed. Figs. 5a and 5b show a comparison of the results for the three refrigerants in the three cities. As noted earlier for supermarket refrigeration systems, refrigerant GWP has a strong impact on LCCP; and as such, the LCCP for refrigerants with higher GWP tends to have a higher sensitivity to charge variation than lower GWP refrigerants, as shown in Fig. 5a. Furthermore, low GWP refrigerants reduce the direct emissions, hence the impact of indirect emissions on LCCP becomes more prevalent. As such, the sensitivity of LCCP to variation in electricity production emission rates becomes more pronounced for low GWP refrigerants, as shown in Fig. 5b. Moreover, for cities with low hourly emission rates for electricity production, such as Seattle, the contribution of direct emissions to total emissions is higher than for other cities. Thus, the LCCP for cities such as Seattle tend to have higher sensitivity to charge variation. It is observed from the results that the trends for Chicago and Miami are very similar. Hence, the difference in climate between each of the cities did not impact the sensitivity of LCCP to changes in refrigerant charge or hourly electricity production emission rates.

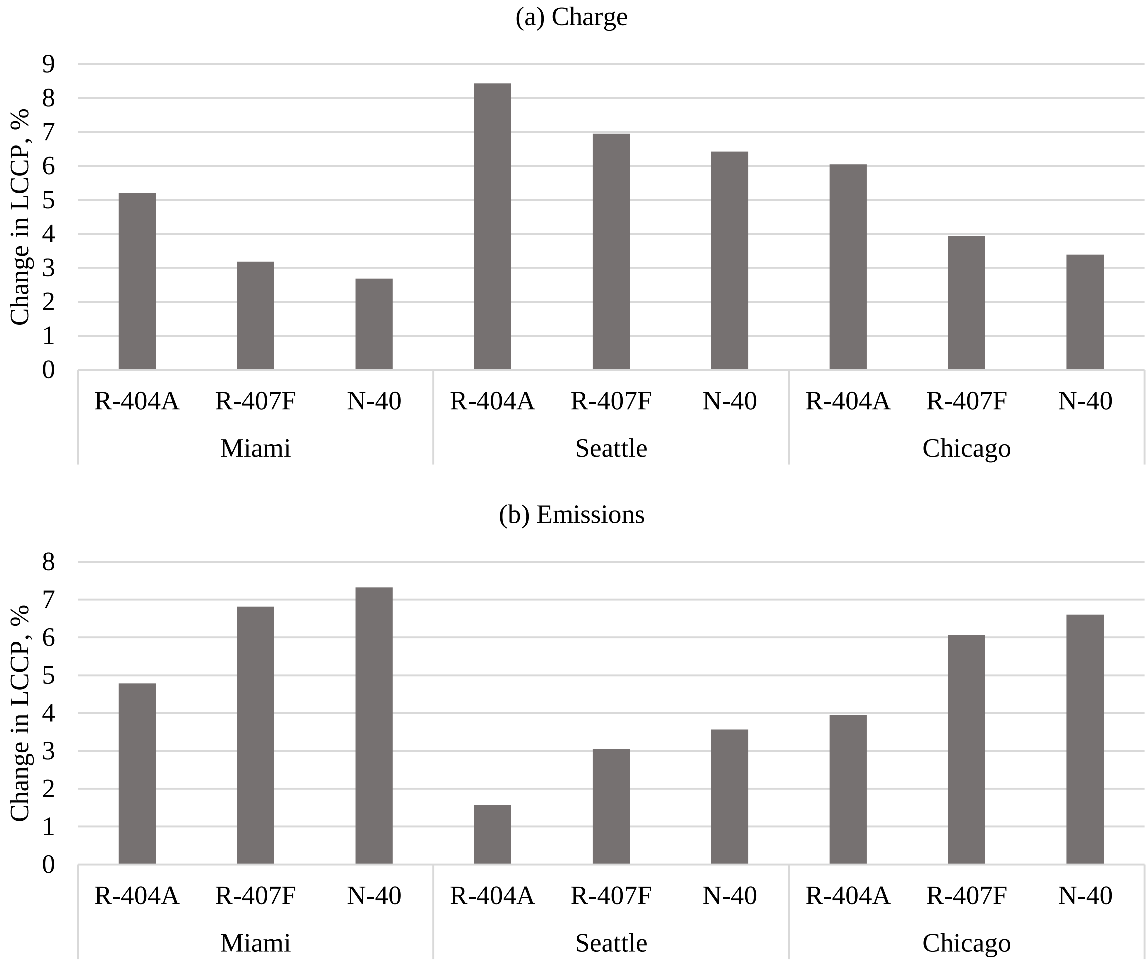

Figure 5: Sensitivity of LCCP to a 10% change in (a) refrigerant charge and (b) electricity production emissions

5.3 Uncertainty Analysis

An uncertainty study was performed on the multiplex DX refrigeration system located in Chicago and Seattle when using R-404A and N-40 to determine the effect of the uncertainty of the inputs (service and annual leakage rates, refrigerant loss at end-of-life, percentage of reused refrigerant, system charge, hourly emission rate for electricity production, and refrigerant's GWP) on the LCCP results. The assumed uncertainties used in our analysis are shown in Table 5.

Table 5: Input uncertainty values

Input	**Uncertainty, %**		
	Case 1	**Case 2**	**Case 3**
Reused refrigerant	20	20	20
Service leakage rate	20	20	20
Refrigerant loss at end-of-life	20	20	20
Annual leakage rate	20	20	20
Charge	5	5	5
Power plant emission	5	5	20
Refrigerant GWP	20	5	5

The resulting uncertainties of the system's total CO_{2eq} emissions, due to uncertainties of the inputs, are shown in Table 6. The partial derivatives of the total emissions with respect to each of the input parameters are shown in Table 7 along with the percentage difference between the derivatives value when using N-40 compared to R-404A. The partial derivatives do not change for any of the three cases listed in Table 5 because they do not depend on the magnitude of uncertainty of the components but rather on the baseline design itself. Thus, changing the location from Chicago to Seattle only causes a change in the partial derivative which depends on the location which is the derivative of the total emissions with respect to the hourly emission rate for electricity production. Also, the results show that shifting to a low GWP refrigerant causes a large drop in the impact of the uncertainty in the inputs related to the direct emissions (service leakage rate, refrigerant loss at end-of-life, annual leakage rate, and system's charge) on the total emissions. This causes the uncertainty in the power plant emissions to be more dominant in the uncertainty of the total emissions of the system. Thus, for the low GWP refrigerant (N-40) in Chicago for case 3, the uncertainty of the system's total emissions is higher than for R-404A.

Table 6: Uncertainties (%) of the system's total CO_{2eq} emissions

Case 1				Case 2				Case 3			
Chicago		Seattle		Chicago		Seattle		Chicago		Seattle	
R-404A	N-40	R-404A	N-40	R-404A	N-40	R-404A	N-40	R-404A	N-40	R-404A	N-40
15.82	9.40	21.91	16.77	10.69	6.76	14.67	11.32	13.15	14.47	14.99	13.26

Table 7: Partial derivatives of the total emissions with respect to each of the input parameters

	Chicago			**Seattle**		
	Partial derivative			**Partial derivative**		
	R-404A	**N-40**	**% difference**	**N-40**	**R-404A**	**% difference**
Reused refrigerant	-23013	-11024	-52.10	-23013	-11024	-52.10
Service leakage rate	54335033	17542099	-67.71	54335033	17542099	-67.71
Refrigerant loss at end-of-life	5433503	1754210	-67.71	5433503	1754210	-67.71
Annual leakage rate	109130322	35304680	-67.65	109130322	35304680	-67.65
Charge	10288	3327	-67.66	10288	3327	-67.66
Power plant emission	14531760	14006147	-3.62	14105519	13612997	-3.49
Refrigerant GWP	3583	3583	0	3583	3583	0.00

6. CONCLUSION

In this paper, a flexible tool for LCCP based design and evaluation of supermarket refrigeration systems was presented. This framework is open-source and can be easily extended to the analysis of other vapor compression technologies. This LCCP tool was used to compare the environmental impact of using three different refrigerants in a supermarket refrigeration system in eight US cities. Comparing the total CO_{2eq} emissions for different cities suggests that N-40 is more environmentally friendly in the different climates for the system investigated. Moreover, the sensitivity analysis showed that shifting towards low GWP refrigerants increases the effect of the hourly emission rate for electricity production on the total system emissions. Finally, an uncertainty analysis was performed showing that using low GWP refrigerants in the system causes a large drop in the impact of the uncertainty in the inputs related to the direct emissions.

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SUPPORTING INFORMATION AVAILABLE

The LCCP tool used in this analysis is available free of charge via the internet at: http://lccp.umd.edu/ornllccp/

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