A COMPARATIVE STUDY ON THE ENVIRONMENTAL IMPACT OF SUPERMARKET REFRIGERATION SYSTEMS USING LOW GWP REFRIGERANTS

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Abstract Supermarket refrigeration systems have high environmental impact due to their large refrigerant charge and high leak rates. Consequently, the interest in using low GWP refrigerants such as carbon dioxide (CO₂) and new refrigerant blends is increasing. In this paper, an open-source Life Cycle Climate Performance (LCCP) framework is presented and used to compare the environmental impact of four supermarket refrigeration systems: a transcritical CO₂ booster system, a cascade CO₂/N-40 system, a combined secondary circuit with central DX N-40/L-40 system, and a baseline multiplex direct expansion system utilizing R-404A and N-40. The study is performed for different climates within the USA using EnergyPlus to simulate the systems' hourly performance. Further analyses are presented such as parametric, sensitivity, and uncertainty analyses to study the impact of different system parameters on the LCCP.

Keywords: LCCP, GWP, alternative refrigerant, supermarket refrigeration, environmental impact

NOMENCLATURE

Symbol	Quantity	Units
E	Energy	kWh/kg
Em	Emissions	Tons CO _{2eq}
Em _R	Emission rate for electricity production	kg CO ₂ /kWh
m	Mass	kg
Life	Lifetime	years
LR	Leak Rate	%
N	Number	
R	Percentage of reused refrigerant	%

Subscripts

acc	Accidents
con	Consumed
direct	Direct
elec	Electric energy consumption
eq	Equivalent
h	Hourly
indirect	Indirect
mat	Material
reaction	Reaction byproduct of the atmospheric breakdown of the refrigerant

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recyc	Recycling
ref	Refrigerant
ref,disp	Refrigerant recycling and disposal at end-of-life
ref,EOL	Refrigerant leakage at end-of-life
ref,leak	Refrigerant leakage
ref,man	Energy used to manufacture the refrigerant
ref,prod	Refrigerant production and transportation
serv	Servicing
sys	System
sys,EOL	Energy required to recycle the system
sys,man	Energy required to manufacture the system
sys,trans	Energy used to transport the system
total	Total

Abbreviations

CO ₂	Carbon dioxide
DX	Direct expansion
GWP	Global warming potential
LCCP	Life cycle climate performance
LT	Low temperature
MAC	Mobile air conditioners
MT	Medium temperature
TMY	Typical Meteorological Year

1. INTRODUCTION

Commercial refrigeration systems have a major negative environmental impact. This is mainly due to their high refrigerant charge leakage, and high electricity consumption. A typical 3300 m² store in the USA consumes 2-3 GWh of energy which results in significant indirect carbon dioxide equivalent (CO_{2eq}) emissions. Furthermore, a typical supermarket using 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). Using high or moderate global warming potential (GWP) refrigerants together with these high refrigerant leak rates contributes to significant direct CO_{2eq} emissions. Methods for reducing the negative environmental impact of commercial refrigeration systems include using low GWP refrigerants, improving the efficiency of the systems, and designing systems (component sizing, refrigerant selection, etc.) with environmental impact as one of the primary performance criterion.

Natural refrigerants tend to have very low GWP, however, the efficiency and overall environmental impact of systems utilizing natural refrigerants need to be evaluated. Many ongoing efforts are pursued to develop suitable low GWP alternative refrigerants for use in commercial refrigeration with a tradeoff 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 collectively create a synergy using HVAC&R 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 with significantly lower GWP than R-404A (Motta, 2011).

Moreover, designing a system while primarily considering its environmental impact requires an evaluation of the system's overall environmental impact as a function of its design parameters. The most comprehensive metric proposed for this evaluation is the system's Life Cycle Climate Performance (LCCP). The LCCP concept was first presented in the report of the Montreal Protocol Technology and Economic Assessment Panel (TEAP) (UNEP/TEAP, 1999). The LCCP of a system represents the total CO_{2eq} global warming impact over the lifetime of the system. The objective of the LCCP analysis is to evaluate the equivalent mass of CO_{2eq} released into the atmosphere due to a refrigeration system's use, throughout its lifetime, from system construction through its operation and 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 as 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 (Arthur D. Little Inc., 2002). In addition, some tools for system evaluation based on LCCP have been presented in the literature. Papasavva et al. (Papasavva, et al., 2010) developed a comprehensive life cycle analysis tool of alternative mobile air conditioners (MACs), GREEN-MAC LCCP, and presented sample results generated from the tool. However, this tool is limited to LCCP analysis of MACs. Also, an LCCP analysis tool for residential heat pumps was presented by Zhang et al. (Zhang, et al., 2011). This tool was specifically developed for residential heat pump analyses.

This paper presents an open-source and modular framework for LCCP-based design of vapor compression systems. A computational tool (computer program) based on this framework is used to compare the LCCP of four supermarket refrigeration systems, in six US cities representing different climate zones. Leak tight and energy efficient systems using CO₂ have been investigated in literature. Among these systems, the transcritical CO₂ booster system, and the cascade system show good potential for having lower total emissions (Abdelaziz, et al., 2012; Rajendran, 2013). Also, the secondary circuit system shows promising energy savings (Southern California Edison, 2004). Thus, in this paper, the N-40/L-40 secondary circuit system is compared with the transcritical CO₂ booster system, the cascade CO₂/N-40 system, and the multiplex direct expansion (DX) utilizing R-404A and N-40. Furthermore, parametric analysis, sensitivity analysis, and uncertainty analysis are performed to provide more in depth understanding of the systems' LCCP.

2. LCCP FRAMEWORK

Figure 1 shows the proposed LCCP framework (Oak Ridge National Laboratory (ORNL), and the University of Maryland College Park (UMCP), 2013). The core module in this framework is the open-source LCCP calculation methodology. This module is connected with 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 interfaces. Due to the modular nature of the framework, any individual module can be replaced with a user-defined module. Hence, the framework is extensible and suitable for the analyses of a variety of systems.

Figure 1: LCCP Framework

The system performance model uses the weather data and calculates the hourly power consumption of the system at rated capacity. In turn, the load model provides the hourly load values. These hourly load and rated power consumption values are then used to calculate the actual hourly energy consumption of the system. The hourly energy consumption is then multiplied by the hourly emission rate for electricity production, obtained from location-specific standardized reference datasets for emissions, Deru and Torcellini (Deru & Torcellini, 2007) was used for hourly emission rate within the USA. Different building energy modeling tools such EnergyPlus (U.S. Department of Energy (DOE), 2012) can be used in the load module to determine the hourly load profile only, or both the hourly load and the system energy consumption. In the latter case, a separate system performance model is not required.

The Typical Meteorological Year (TMY) data from the National Solar Radiation Data Base (National Renewable Energy Laboratory (NREL), 2012) is used as default weather data. These datasets include hourly values for dry-bulb temperature, dew-point temperature, and relative humidity. Finally, 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) (Intergovernmental Panel on Climate Change (IPCC), 2013). The GWP values of other refrigerants which are not listed in AR5 were obtained from the AHRTI report (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.

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

$$Em_{ref,leak} = m_{ref} \times Life_{sys} \times LR_{annual} \times GWP \quad (2)$$

$$Em_{acc} = m_{ref} \times Life_{sys} \times LR_{acc} \times GWP \quad (3)$$

$$Em_{serv} = N_{serv} \times m_{ref} \times LR_{serv} \times GWP \quad (4)$$

$$Em_{ref,EOL} = LR_{ref,EOL} \times m_{ref} \times GWP \quad (5)$$

$$Em_{ref,prod} = LR_{ref,prod} \times m_{ref} \times GWP \quad (6)$$

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.

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

$$Em_{sys,man} = \sum_{mat} m_{mat} \times CO_{2eq,mat} \quad (8)$$

$$Em_{ref,man} = m_{ref} \times (1 + Life_{sys} \times LR_{annual} - R) \times CO_{2eq,ref} \quad (9)$$

$$Em_{sys,EOL} = \sum_{mat} E_{recyc,mat} \times m_{mat} \times CO_{2eq,mat} \quad (10)$$

$$Em_{sys,elec} = Life_{sys} \times \sum_{n=0}^{8760} E_{h,con} \times Em_R \quad (11)$$

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 4181 m² 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). The analysis is done for six US cities representing different climate zones, as shown in Table 1. Moreover, the system lifetime is assumed to be 20 years with service interval of 2 years. 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 the remaining leakage rates that appear in Eq. (1-12), but which do not have a value mentioned in this section, are assumed to be zero. The GWP and blend composition for the different refrigerants is shown in Table 2 where the GWP of the refrigerants are obtained from 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)	Average Hourly Emission Rate for Electricity Production (kgCO ₂ /kWh)
1A	Miami, FL	24.9	0.678
2B	Phoenix, AZ	23.8	0.757
3B	Los Angeles, CA	17.3	0.351
4B	Albuquerque, NM	14.2	1.1
5A	Chicago, IL	10.0	0.638
8	Fairbanks, AK	-2.1	0.774

Table 2: Blend composition and GWP values of the used refrigerants

Refrigerant	Composition (Mass %)	GWP
CO ₂	CO ₂ (100)	1
N-40	R-32/R-125/R-134a/R-1234yf (25/25/20/30)	1273
L-40	R-32/R-152a/R-1234yf/R-1234ze (40/10/20/30)	285
R-404A	R-125/R-134a/R-143a (44/4/52)	3943

4.1. Multiplex DX System (S1)

The multiplex DX system, shown in Figure 2a, consists of a medium temperature (MT)/low temperature (LT) direct expansion (DX) compressor rack with mechanical subcooling and an air-cooled condenser. Two such systems are used to satisfy the refrigeration loads of the supermarket, and the refrigeration load and refrigerant charge for each system is given in Table 3. This system is analyzed with R-404A and N-40A as working fluids.

4.2. Cascade N-40/CO₂ System (S2)

The cascade N-40/CO₂ system, shown in Figure 2b, consists of a primary DX system using the refrigerant N-40, which cools a LT CO₂ DX system and a MT CO₂ secondary loop. The cascade system rejects heat through an air-cooled condenser. The MT loads are cooled with a pumped CO₂ secondary loop while the LT loads are cooled by the LT CO₂ DX system. Two such systems are used to satisfy the refrigeration loads of the supermarket, and the refrigeration load and refrigerant charge for each system are given in Table 3.

4.3. Transcritical CO₂ Booster System (S3)

In the transcritical CO₂ Booster System, shown in Figure 2c, both the MT and LT loads are served by direct expansion of CO₂. The heat rejection from the system occurs either supercritically or subcritically, depending upon the outdoor ambient temperature, through an air-cooled gas cooler. Two such systems are used to satisfy the refrigeration loads of the supermarket, and the refrigeration load and refrigerant charge for each system are given in Table 3.

Figure 2: Systems' schematic: (a) S1, (b) S2, and (b) S3

4.4. Secondary (MT) / Central DX (LT) System (S4)

For the secondary circuit system, the MT loads are served by a secondary circuit which uses propylene glycol cooled by a DX system using L-40. The LT loads are satisfied with a separate centralized DX system utilizing N-40. The refrigeration load and refrigerant charge for each compressor rack is given in Table 3.

Table 3: Systems' load and charge

System	Subsystem	Refrigeration Load (kW)	Refrigerant Charge (kg)
S1	Multiplex DX System 1	MT: 167.1, LT: 64.6	1038
	Multiplex DX System 2	MT: 52.8, LT: 23.4	340
	Total	307.9	1378
S2	Cascade System 1	MT: 167.1, LT: 64.6	N-40: 625, CO ₂ : 340
	Cascade System 2	MT: 52.8, LT: 23.4	N-40: 205, CO ₂ : 110
	Total	307.9	N-40: 830, CO₂: 450
S3	CO ₂ Booster System 1	MT: 118.6, LT: 64.6	520
	CO ₂ Booster System 2	MT: 101.2, LT: 23.4	170
	Total	307.9	690
S4	MT1	167.1	209
	MT2	52.8	66
	LT1	64.6	290
	LT2	23.4	104
	Total	307.9	669

4.5. EnergyPlus Modeling Assumptions

In this section, some of the modeling assumptions used in the EnergyPlus are provided.

- The evaporating temperatures for the three refrigeration system types are shown in Table 4. Each system is modeled with two MT suction groups and two LT suction groups. It was assumed that the evaporating temperatures of the CO₂-based systems were 1.1°C higher than that of the HFC-based systems due to the better transport properties of carbon dioxide.

Table 4: Evaporating temperatures for the three refrigeration systems

System	Compressor Rack	Temperature Level	Evaporating Temperature (°C)
S1	Rack A	MT	-2.80
	Rack B	LT	-20.0
	Rack C	MT	-2.80
	Rack D	LT	-28.3
S2	Rack A	MT	-1.70
	Rack B	LT	-18.0
	Rack C	MT	-1.70
	Rack D	LT	-27.2
S3	Rack A	MT	-1.70
	Rack A	LT	-18.0
	Rack B	MT	-1.70
	Rack B	LT	-27.2

- For systems S1 and S2, the suction line pressure drop was assumed to be 17 kPa (2.5 psi) while the discharge line pressure drop was assumed to be 8.5 kPa (1.2 psi). The suction gas temperature at the compressor inlet was assumed to be the saturated evaporator temperature plus the display case superheat. The display case superheat was assumed to be 4 K for systems S1 and S2 and 10 K for system S3.
- System S1 contains a subcooler for each LT compressor rack. The temperature of the liquid refrigerant exiting the subcooler was set to 10°C (50°F). No subcoolers were used in the cascade system (system S2). System S3 contains a liquid-suction heat exchanger just after the gas cooler. The effectiveness of this heat exchanger was assumed to be 0.4.
- The difference between the saturated condensing temperature and the ambient air for systems S1 and S2 were approximately 4 K for ambient temperatures greater than or equal to 20°C (68°F). In addition, the minimum condensing temperature for Systems S1 and S2 was set at 22°C (72°F), which is typical of R-404A DX systems today due to the limitations of widely used thermostatic expansion valves at low condensing pressures. However, it is noted that the use of electric

expansion valves (EEVs) would allow for lower condensing temperatures in DX or cascade systems. A lower condensing temperature, around 10°C for example, would significantly improve the COP of these systems in cold climates. No subcooling was assumed at the exit of the condensers.

- For system S3, it was assumed that the temperature difference between the gas cooler outlet and the ambient air was 3 K for transcritical operation and 10 K for subcritical operation. During subcritical operation, the minimum condensing temperature for System S3 was set at 10°C (50°F). Note that due to the high operating pressures of CO₂ systems, it is possible to have an acceptable pressure drop across the expansion valves at lower condensing temperatures than would be possible with HFC-based systems that use thermostatic expansion valves.
- For all systems, the performance of the compressors was determined from manufacturers' compressor maps. The compressors used in the simulations are listed in Table 5. Inefficiencies occurring during part load operation were ignored. The performance of the N40 compressors was based on R404A compressor performance by assuming that N40 capacity was 100% of R404A capacity and N40 power was 93% of R404A power.
- For all systems, the fan power (for evaporators and condensers/gas cooler) was taken into account.

Table 5: Compressor models used in simulations

Manufacturer	Refrigerant	Temperature Level	Model
Copeland (Emerson)	R-404A N-40 L-40	MT	3DA3R10ML
			4DBXR20ML
			4DJ3R28ML
			ZF13KVE
Bitzer	CO ₂	LT	2DA3F23KL
			4DL3F63KE
			4HTC-15K
			2FSL-4K
			2HSK-3K

5. RESULTS AND DISCUSSION

5.1. LCCP Analysis

Figure 3 shows the direct emissions of the four refrigeration systems (S1, S2, S3, and S4). The direct emissions are dependent on the system refrigerant (GWP of refrigerant), and charge mass and are not affected by the system location. Hence, S3 has the lowest direct emissions due to its low refrigerant GWP and charge mass. Although S4 has slightly lower charge mass than S3, it has higher direct emissions than S3 as S4 utilizes a refrigerant with a much higher GWP. The baseline S1 has the highest direct emissions as it has the highest charge using and the highest GWP refrigerant (R-404A).

Figure 3: Direct emissions of the four refrigeration systems

Figure 4 shows the indirect emissions in the six studied cities for the various refrigeration systems. It is clear that while system location does not affect the direct emissions, it does affect the indirect emissions. This is due to differences in the system performance, the weather data (leading to different hourly system power

draw) and the hourly emission rate for electricity production. In Figure 4, it is noticed that in cold climates such as Fairbanks, the energy consumption of system S3 is much closer to the other systems than in warmer climates such as Miami. This is because the CO₂ does not perform in warm climates as efficiently as in cold climates as shown in Figure 5 (the figure was generated using weather data for Chicago, IL). Thus, system S3 tends to have higher indirect emissions than the other systems in warmer climates. Also, it is worth noting that the indirect emissions in Los Angeles are much lower than the other cities for all systems although it might have higher annual electricity consumption (e.g. than Fairbanks). This is because the hourly emission rate for electricity production is low for Los Angeles as shown in Table 1. It is recognized that for all climates, the secondary circuit system (S4) tend to have the lowest electricity consumption and hence indirect emissions. On the other hand, almost for all climates, especially the hot climates such as Miami and Phoenix, the transcritical CO₂ booster system (S3) results in higher electricity consumption and as such high indirect emissions.

Figure 4: Total indirect emissions and annual electricity consumption of the four refrigeration systems

Figure 5: variation of the COP with the ambient temperature

Figure 6 shows the total emissions in the six studied cities for the various refrigeration systems. For cities in cold and temperate climates, the slightly higher indirect emissions of the transcritical CO₂ booster system are

outweighed by its lower direct emissions. Thus, for these climates, S3 has the lowest total emissions. On the other hand, for cities in hot climates such as Miami and Phoenix the higher direct emissions of the secondary circuit system (compared to S3) are outweighed by its lower indirect emissions. Hence, S4 is more environmentally friendly in the hot climates. Overall, the secondary circuit system offers a good trade-off between emissions and electricity consumption making it more attractive for most climates. On the other hand, the multiplex DX system utilizing R-404A has the highest total emissions.

Figure 6: Total emissions of the four refrigeration systems

5.2. Parametric Analysis

A parametric analysis of the effect of changing the annual leak rate of the system on the total emissions of systems S1, S3 and S4 in Chicago is performed. Figure 7 shows a comparison of the results for the three systems. The direct emissions are the major contributor for LCCP CO₂eq emissions in supermarket systems, therefore, using lower GWP refrigerants, or more leak-tight systems result in considerable decrease in the system's total emissions. For CO₂ systems, such as S3 the impact of reducing the annual leak rate is negligible. On the other side, for systems using refrigerants with high or moderate GWP values (such as S1 utilizing R404-A), reducing the annual leak rate has large impact on the total emissions. As previously discussed, for the base annual leakage rate (10%) in Chicago, S4 has higher total emissions than S3 although S4 has lower indirect emissions than S3. This is because of the much lower direct emissions, mainly due to annual leak rate, of S3 compared to S4. As shown in Figure 7, if the annual leak rate is lower than 2%, the higher direct emissions of the S4 compared to S3 is outweighed by its lower indirect emissions. Hence, for low annual leak rates, S4 tends to become more environmentally friendly than all other studied refrigeration systems in all climates.

Figure 7: Sensitivity analysis of refrigerant charge and electricity production emissions

5.3. Sensitivity Analysis

A sensitivity analysis is performed to determine 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 systems S1, and S3 in Miami, and Los Angeles. Figs. 8a and 8b show a comparison of the results for the two systems in the two cities. As noted earlier for supermarket refrigeration systems, refrigerant GWP and charge mass have a strong impact on LCCP. Thus, the LCCP for systems with higher direct emissions (i.e. utilizing refrigerants with higher GWP, or having larger charge mass) tends to be more sensitive to charge variation than systems with lower direct emissions (i.e. utilizing lower GWP refrigerants or having smaller charge mass), as shown in Figure 8a. Moreover, using low GWP refrigerants or smaller system charge reduces 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 noticeable for low GWP refrigerants or smaller charge mass systems, as shown in Figure 8b. Moreover, for cities with low hourly emission rates for electricity production, such as Los Angeles, the contribution of direct emissions to total emissions is higher than for other cities. Thus, the LCCP for cities such as Los Angeles tend to have higher sensitivity to charge variation.

Figure 8: Sensitivity of LCCP to a 10% change in (a) refrigerant charge and (b) electricity production emissions

5.4. Uncertainty Analysis

An uncertainty study is performed on S1 located in Chicago and Los Angeles when using R-404A and N-40 to determine the effect of the uncertainty of the inputs on the LCCP results. The inputs included in the study are the 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. The analysis is performed for three different cases. For the 3 cases the uncertainty values for reused refrigerant, service leakage rate, refrigerant loss at end-of-life, and annual leakage rate are assumed at 20%, and the charge uncertainty is assumed to be 5%. The power plant emission, and the refrigerant GWP uncertainties were varied. For cases 1, 2, and 3 the power plant emission uncertainty are 5%, 5%, and 20% respectively, and the refrigerant GWP uncertainty was 20%, 5%, and 5% respectively.

The resulting uncertainties of the system's LCCP, as a result of 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 accompanied by the percentage difference between the derivatives values when utilizing N-40 compared to R-404A. The partial derivatives do not change for any of the three cases. This is simply because the derivatives do not depend on the magnitude of uncertainty of the inputs 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 such as the derivative of the total emissions with respect to hourly emission rate for electricity production. Also, the results show that shifting to a low GWP refrigerant causes a noticeable 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 results in more dominant impact of the power plant emissions uncertainty on the uncertainty of the total system emissions. 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. Finally, performing the same uncertainty analysis for S3

in Los Angeles results in LCCP uncertainty of 5%, 5%, and 19.98% for cases 1, 2, and 3, respectively. This is due to the small direct emissions of this system which makes the uncertainty in the power plant emissions much more dominant than in the case of other systems. This causes the uncertainty in the transcritical CO₂ booster system's LCCP to follow the value of the uncertainty in the power plant emissions.

Table 6: Uncertainties (%) of the system's LCCP

Case 1				Case 2				Case 3			
Chicago		Los Angeles		Chicago		Los Angeles		Chicago		Los Angeles	
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	18.64	12.17	10.69	6.76	12.52	8.40	13.15	14.47	13.68	13.45

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	-2.3E+04	-1.1E+04	-52.10	-2.3E+04	-1.1E+04	-52.10
Service leakage rate	5.4E+07	1.8E+07	-67.71	5.4E+07	1.8E+07	-67.71
Refrigerant loss at end-of-life	5.4E+06	1.8E+06	-67.71	5.4E+06	1.8E+06	-67.71
Annual leakage rate	1.1E+08	3.5E+07	-67.65	1.1E+08	3.5E+07	-67.65
Charge	1.0E+04	3.3E+03	-67.66	1.0E+04	3.3E+03	-67.66
Power plant emission	1.45E+07	1.40E+07	-3.62	1.61E+07	1.55E+07	-3.36
Refrigerant GWP	3.6E+03	3.6E+03	0	3.6E+03	3.6E+03	0

6. CONCLUSION

A flexible tool for LCCP based design and evaluation of supermarket refrigeration systems was developed in this paper. This LCCP framework is open-source and can be easily extended to the analysis of other refrigeration and vapor compression technologies. This LCCP tool was used to compare the environmental impact of four different supermarket refrigeration systems in six US cities. Comparing the total emissions for different cities suggests that the transcritical CO₂ booster system has the lowest CO₂ equivalent emissions, according to this analysis, in cold and temperate climates with annual leak rate higher than 2% although it has higher energy consumption. Also, the secondary circuit N-40/L-40 system is found to offer a good balance between emissions and electricity consumption for hot climates with annual leak rate of 10%, and for all climates for annual leak rate less than 2%. The parametric analysis showed that shifting towards low GWP refrigerants decreases the effect of the annual leak rate on the total system emissions. Moreover, the sensitivity analysis showed that shifting towards low GWP refrigerants, or more charge conservative systems 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, or more charge conservative systems causes a noticeable drop in the impact of the uncertainty in the inputs related to the direct emissions.

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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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